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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
UTILITY APPLICATION AND FEE TRANSMITTAL (1.53(b))

ASSISTANT COMMISSIONER FOR PATENTS
BOX PATENT APPLICATION
Washington, D.C. 20231

Sir:

Transmitted herewith for filing is the patent application of

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Additional inventors are listed on a separate sheet

For: EFFICIENT AND COMPACT SUBGROUP TRACE REPRESENTATION ("XTR")

Enclosed Are:

36 page(s) of specification
1 page(s) of Abstract
5 page(s) of claims
11 sheets of Formal Informal drawings

6 page(s) of Declaration and Power of Attorney

Unsigned
 Newly Executed
 Copy from prior application
 Deletion of inventors including Signed Statement under 37 C.F.R. §1.63(d)(2)

Incorporation by Reference:

The entire disclosure of the prior application, from which a copy of the combined Declaration and Power of Attorney is supplied herein, is considered as being part of the disclosure of the accompanying application and is incorporated herein by reference.

Microfiche Computer Program (Appendix)

page(s) of Sequence Listing

computer readable disk containing Sequence Listing

Statement under 37 C.F.R. §1.821(f) that computer and paper copies of the Sequence Listing are the same

Assignment Papers (assignment cover sheet and assignment documents)

A check in the amount of \$40.00 for recording the Assignment

Charge the Assignment Recordation Fee to Deposit Account No. 13-4503, Order No. _____

Assignment Papers filed in the parent application Serial No. _____

Certification of chain of title pursuant to 37 C.F.R. §3.73(b)

Priority is claimed under 35 U.S.C. §119 for:
Application No(s). _____, filed _____, in _____ (country).

Certified Copy of Priority Document(s) [_____]

filed herewith

filed in application Serial No. _____, filed _____.

English translation document(s) [_____]

filed herewith

filed in application Serial No. _____, filed _____.

Priority is claimed under 35 U.S.C. §119(e) for:
Provisional Application No. _____, filed _____.

Priority is claimed under 35 U.S.C. §120 for:
Application No(s). _____, filed _____, in _____.

Information Disclosure Statement

Copy of [_____] cited references

PTO Form-1449

References cited in parent application Serial No. _____, filed _____.

Preliminary Amendment

Return receipt postcard (MPEP 503)

This is a continuation divisional continuation-in-part of prior application serial no. _____, filed _____.

Cancel in this application original claims _____ of the parent application before calculating the filing fee. (At least one original independent claim must be retained for filing purposes.)

A Preliminary Amendment is enclosed. (Claims added by this Amendment have been properly numbered consecutively beginning with the number following the highest numbered original claim in the prior application.)

The status of the parent application is as follows:

- A Petition for Extension of Time and a Fee therefor has been or is being filed in the parent application to extend the term for action in the parent application until ____.
- A copy of the Petition for Extension of Time in the co-pending parent application is attached.
- No Petition for Extension of Time and Fee therefor are necessary in the co-pending parent application.
- Please abandon the parent application at a time while the parent application is pending or at a time when the petition for extension of time in that application is granted and while this application is pending has been granted a filing date, so as to make this application co-pending.
- Transfer the drawing(s) from the parent application to this application
- Amend the specification by inserting before the first line the sentence:
This is a continuation of co-pending application Serial No. _____, filed _____.

| I. CALCULATION OF APPLICATION FEE | | | | |
|--|--------------|---|-----------------|------------------------------|
| | Number Filed | Number Extra | Rate | Basic Fee \$690.00/345.00 |
| Total Claims | 24- 20 = | 4x | \$18.00/\$9.00 | \$ 72.00 |
| Independent Claims | 4- 3 = | 1x | \$78.00/\$34.00 | \$ 78.00 |
| <input type="checkbox"/> Multiple Dependent Claims | | If marked, add fee of \$260.00 (\$130.00) | | \$ 0.00 |
| | | | | TOTAL: \$ 840.00 |

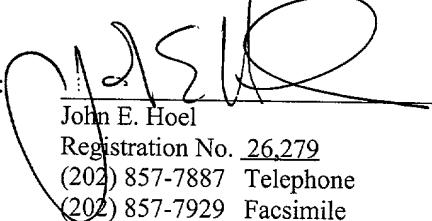
- A statement claiming small entity status is attached or has been filed in the above-identified parent application and its benefit under 37 C.F.R. §1.28(a) is hereby claimed. Reduced fees under 37 C.F.R. §1.9 (f) paid herewith \$_____.
- A check in the amount of \$ _____ in payment of the application filing fees is attached.
- Charge fee to Deposit Account No. 13-4500 Order No. 0225-4188. A DUPLICATE COPY OF THIS SHEET IS ATTACHED.

The Assistant Commissioner is hereby authorized to charge any additional fees which may be required for filing this application pursuant to 37 CFR §1.16, including all extension of time fees pursuant to 37 C.F.R. § 1.17 for maintaining copendency with the parent application, or credit any overpayment to Deposit Account No. 13-4500 Order No. 0225-4188. A DUPLICATE COPY OF THIS SHEET IS ATTACHED.

Respectfully submitted,
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Dated: 02/07/00

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TITLE OF THE INVENTION

Efficient And Compact Subgroup Trace Representation ("XTR")

INVENTORS

Arjen K. Lenstra and Eric. R. Verheul

RELATED PATENT APPLICATIONS

The following copending US Patent applications are directed to related inventions and are incorporated herein by reference.

US Patent application entitled "Cyclotomic Polynomial Construction Of Discreet Logarithm Cryptosystems Over Finite Fields", Application No. 08/800,669, Filed: February 14, 1997, Applicant: Arjen K. Lenstra.

US Patent application entitled "Generating RSA Moduli Including A Predetermined Portion", Application No. 09/057,176, Filed: April 8, 1998, Applicant: Arjen K. Lenstra.

BACKGROUND OF THE INVENTION

Field of the Invention

The invention disclosed broadly relates to public key cryptography and more particularly relates to improvements in key generation and cryptographic applications in public key cryptography.

Related Art

The generation of a modulus as part of a public key according to the Rivest-Shamir-Adleman (RSA) cryptographic method is described in U.S. Patent No. 4,405,829 (Rivest et al.), "Cryptographic Communications System and Method", the disclosure of which is hereby incorporated by reference. In a set-up phase of the RSA scheme, a participant picks two prime numbers, p and q, each having a selected number of bits, such as 512

bits, with p not equal to q. The participant keeps p and q secret. The participant computes an RSA modulus n, with $n = p * q$. When p and q each have 512 bits, n has 1023 or 1024 bits. The participant picks an RSA exponent e that has no factors in common with $(p-1)(q-1)$. For efficiency purposes, the RSA exponent e is often chosen of much shorter length than the RSA modulus. When the RSA modulus n has 1024 bits, the RSA exponent e typically has at most 64 bits. The owning participant makes the public key (n, e) available to other participants.

During operational use of the RSA scheme, other participants use the public key (n, e) to encrypt messages for the participant which owns that key. The owning participant is able to decrypt messages encrypted with the public key (n, e) due to possession of the secret prime numbers p and q.

Participants must store not only the public key of other participants, but also identifying information such as the name, address, account number and so on of the participant owning each stored public key. There are problems with this situation.

One problem with the present technique for using the RSA encryption scheme is that, although the RSA modulus n is 1024 bits, the amount of security provided actually corresponds to only 512 bits, since an attacker who knows one of p and q can readily obtain the other of p and q. Instead of having to store 1024 bits to obtain 512 truly secure bits, it is desirable to store far fewer bits, such as approximately 512 bits, to obtain the 512 truly secure bits.

Another problem with the present technique is that the long bit-length of the public keys imposes a significant bandwidth load on telecommunications devices, such as wireless telephone sets. It is desirable to reduce the amount of bandwidth load as much as possible.

Generating RSA moduli having a predetermined portion has been considered by Scott A. Vanstone and Robert J. Zuccherato in "Short RSA Keys and Their Generation", J. Cryptology, 1995, volume 8, pages 101-114, the disclosure of which is hereby incorporated by reference.

In "Finding a Small Root of a Bivariate Integer Equation; Factoring with High Bits Known", U. Maurer ed., EUROCRYPT '96 Proceedings, pages 178-189, Springer Verlag 1996, the disclosure of which is hereby incorporated by reference, Don Coppersmith has analyzed the security of the Vanstone methods, and found that all but one of Vanstone's methods provide inadequate security. Specifically, for the Vanstone methods having predetermined high order bits, the RSA modulus n is generated in such a way that somewhat more than the high order $((1/4)\log_2 n)$ bits of p are revealed to the public,

which enables discovery of the factorization of the RSA modulus n, thus leaving the scheme vulnerable to attack.

SUMMARY OF THE INVENTION

The invention disclosed provides improvements in key generation and cryptographic applications in public key cryptography, by both reducing: 1) the bit-length of public keys and other messages, thereby reducing the bandwidth requirements of telecommunications devices, such as wireless telephone sets, and 2) the computational effort required to encrypt/decrypt and to generate/verify digital signatures.

The method of the invention determines a public key having a reduced length and a factor ρ , using $GF(p^2)$ arithmetic to achieve $GF(p^6)$ security, without explicitly constructing $GF(p^6)$. The method includes the step of selecting a number ρ and a prime number q that is a divisor of $\rho^2 - \rho + 1$. Then the method selects an element g of order q in $GF(p^6)$, where g and its conjugates can be represented by B , where $F_g(X) = X^3 - BX^2 + B^pX - 1$ and the roots of $F_g(X)$ are g, g^{p-1} , and g^p . Then the method represents the powers of g using their trace over the field $GF(p^2)$. The method then selects a private key. The method then computes a public key as a function of g and the private key. The public key can be used to encrypt a message and the public and private key can be used to decrypt the message. The public and private key can be used for signing a message and the public key can be used for verifying the signature. A Diffie Hellman key exchange or other related scheme can be conducted using the public key generated by the method. The resulting invention reduces the bit-length of public keys and other messages, thereby reducing the bandwidth requirements of telecommunications devices, and reduces the computational effort required to encrypt/decrypt and to generate/verify digital signatures.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a diagram of an example network in which the invention can be carried out.

Figure 2 is a functional block diagram of an example server computer in the network of Figure 1, in which the invention can be carried out.

Figure 3 is a functional block diagram of an example client computer in the network of Figure 1, in which the invention can be carried out.

Figure 4 is a flow diagram of the method performed in a server and/or a client in the network of Figure 1, in accordance with the invention.

Figure 5 is a flow diagram of the preferred embodiment of the method for selection of "p", and "q", as shown in section 2.1.

Figure 6 is a flow diagram of the arithmetic method to support key generation, as shown in section 2.4.4.

Figure 7 is a flow diagram of the method of key generation, as shown in section 3.3.8.

Figure 8 is a flow diagram of the method of Diffie Hellman key exchange, as shown in section 4.1, using keys generated by the method of Figure 7.

Figure 9 is a flow diagram of the method of ElGamal encryption, as shown in section 4.2, using keys generated by the method of Figure 7.

Figure 10A is a flow diagram of the arithmetic method to support generating digital signatures, as shown in section 2.5.3.

Figure 10B is a flow diagram of the method of generating digital signatures, as shown in section 4.3., using keys generated by the method of Figure 7.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The Network and System Environment of the Invention

The invention is a method, system, computer program, computer program article of manufacture, and business method for providing improvements in key generation and cryptographic applications in public key cryptography, by both reducing: 1) the bit-length of public keys and other messages, thereby reducing the bandwidth requirements of telecommunications devices, such as wireless telephone sets, and 2) the computational effort required to encrypt/decrypt and to generate/verify digital signatures.

Figure 1 is a diagram of an example network in which the invention can be carried out. The method of the invention can be performed, for example, in a server computer connected over a network to a client computer. The method can also be performed, for example, in a client computer. Figure 1 shows a server computer 102 connected over the Internet network 104 to three client computers, the personal computer 106, the main frame computer 108, and a microprocessor in the mobile phone client 130. The mobile phone client 130 is connected via the mobile telephone switching office 110 and the radio frequency base station 120 to the network 104. A database 112 is connected to the server 102, which stores public keys labeled (1), (2), and (3). Public key (1) was generated, in accordance with the method of the invention, in the personal computer client 106, and was transmitted over the network 104 to the server 102, for storage in the database 112. Public key (2) was generated, in accordance with the method of the invention, in the main frame client 106, and was transmitted over the network 104 to the server 102, for storage in the database 112. Public key (3) was generated, in accordance with the method of the invention, in the microprocessor of the mobile phone client 130, and was transmitted to the base station 120 over its radio frequency link, and via the mobile telephone switching office 110 and the network 104 to the server 102, for storage in the database 112. Public key (4) was generated, in accordance with the method of the invention, in the server computer 102, and was transmitted over the network 104 to each of the clients 106, 108, and 130. Each client 106, 108, and 130 generated, in accordance with the method of the invention, a private key respectively labeled (1), (2), and (3) which remains stored in the respective client. The server 102 generated, in accordance with the method of the invention, a private key labeled (4) which remains stored in the server.

Figure 2 is a functional block diagram of an example server computer in the network of Figure 1, in which the invention can be carried out. The server computer 102 includes a memory 202 connected by the bus 204 to the database 112, a hard drive 206, a CPU processor 208, and a network interface card 210 which is connected to the Internet network 104. The memory 202 includes an input buffer 232 and an output buffer 234. The memory 202 also includes a "p" buffer 236, a "q" buffer 238, a "g" buffer 240, and a "B" buffer 242. See sections 1, 2, and 3, below, for a discussion of the values "p", "q", "g", and "B". The memory 202 also includes a private key buffer 244, and a public key buffer 246. The memory 202 also includes a key generation program 400, whose flow diagram is shown in Figure 4, which operates in accordance with the method of the invention. The memory 202 also includes an encryption program 250 that uses the keys generated by the key generation program 400. The method of ElGamal encryption is described in section 4.2. The memory 202 also includes a digital signature signing and verifying program 252 that uses the keys generated by the key generation program 400. The arithmetic method to support generating digital signatures is described in section 2.5.3 and the method of generating digital signatures is described in section 4.3. The memory 202 also includes a key exchange program 254 that uses the keys generated by the key generation program 400. The method of Diffie Hellman key exchange is described in section 4.1. The memory 202 also includes an operating system program 220. The programs stored in the memory 202 are sequences of executable steps which, when executed by the CPU processor 208, perform the methods of the invention.

Figure 3 is a functional block diagram of an example client computer in the network of Figure 1, such as the client 106. The client computer 106 includes a memory 302 connected by the bus 304 to the display interface 314, the keyboard and mouse interface 312, a hard drive 306, a CPU processor 308, and a network interface card 310 which is connected to the Internet network 104. The memory 302 includes an input buffer 332, an output buffer 334, a "p" buffer 336, a "q" buffer 338, a "g" buffer 340, a "B" buffer 342, a private key buffer 344, and a public key buffer 346. The memory 302 also includes the key generation program 400, whose flow diagram is shown in Figure 4, which operates in accordance with the method of the invention. The memory 302 also includes the encryption program 250 that uses the keys generated by the key generation program 400. The memory 302 also includes a digital signature signing and verifying program 252 that uses the keys generated by the key generation program 400. The memory 302 also includes a key exchange program 254 that uses the keys generated by the key generation program 400. The memory 302 also includes an operating system program 320 and a

browser program 106'. The programs stored in the memory 302 are sequences of executable steps which, when executed by the CPU processor 308, perform the methods of the invention.

Figure 4 is a flow diagram of the method performed in either the server computer 102 of Figure 2, or in the clients 106, 108, and/or 130 in accordance with the invention. Program 400 is a sequence of executable steps that embody the method of Figure 4. The method begins at 402 with the step 404 of selecting "q" and "p". The method continues with the step 406 of selecting "g". Then the method continues with the step 408 of representing the powers of "g" using their trace. Then the method continues with the step 410 of selecting a private key. Then the method continues with the step 412 of computing a public key as a function of "g" and the private key. See sections 1, 2, and 3, below, for a discussion of the values "p", "q", and "g". Finally, the method concludes with the step 414 of using the public key and the private key in encryption and decryption, in digital signature signing and verification, and in key exchange and related applications. See section 4, below, for a discussion of these applications.

1. Introduction

The well known Diffie-Hellman (DH) key agreement protocol was the first practical solution to the key distribution problem, allowing two parties that have never met to establish a shared secret key by exchanging information over an open channel. In the basic DH scheme the two parties agree upon a generator g of the multiplicative group $\text{GF}(p)^*$ of a prime field $\text{GF}(p)$ and they each send a random power of g to the other party (cf. Section 4 for a full description). Thus, assuming both parties know p and g , each party transmits about $\log_2(p)$ bits to the other party.

In [4] it was suggested that finite extension fields can be used instead of prime fields, but no direct computational or communication advantages were implied. In [8] a variant of the basic DH scheme was introduced where g generates a relatively small subgroup of $\text{GF}(p)^*$ of prime order q . This considerably reduces the computational cost of the DH scheme, but has no effect on the number of bits to be exchanged. In [2] it was shown for the first time how the use of finite extension fields and subgroups can be combined in such a way that the number of bits to be exchanged is reduced by a factor 3. More specifically, it was shown that elements of an order q subgroup of $\text{GF}(p^6)^*$ can be represented using $2 \cdot \log_2(p)$ bits if q divides $p^2 - p + 1$. Despite its communication

efficiency, the method of [2] is rather cumbersome and computationally not particularly efficient.

In this paper we present a greatly improved version of the method from [2] that achieves the same communication advantage at a much lower computational cost. Furthermore, we prove that using our method in cryptographic protocols does not affect their security. The best attacks we are aware of are Pollard's rho method in the order q subgroup, or the Discrete Logarithm variant of the Number Field Sieve in the full multiplicative group $\text{GF}(p^6)^*$. With primes p and q of about $1024/6 \approx 170$ bits the security of our method is equivalent to traditional subgroup systems using 170-bit subgroups and 1024-bit finite fields. But our subgroup elements can be represented using only about $2*170$ bits, which is substantially less than the 1024-bits required for their traditional representation. The amount of computation required by a full exponentiation in our method is about the same as the time required by a full scalar multiplication in a 170-bit Elliptic Curve cryptosystem, and thus substantially less than the time required by a full 1024-bit RSA exponentiation. As a result our method may be regarded as a compromise between RSA and Elliptic Curve cryptosystems (ECC). We get security similar to RSA for much smaller public key sizes than RSA (though somewhat larger than ECC public keys), but we are not affected by the uncertainty of ECC security. Furthermore, key selection for our method is trivial compared to RSA, and certainly compared to ECC.

Apart from its performance advantages, the most intriguing and innovative aspect of our method is that it is the first method we are aware of that uses $\text{GF}(p^2)$ arithmetic to achieve $\text{GF}(p^6)$ security, without explicitly constructing $\text{GF}(p^6)$. Denote by g an element of order $q > 3$ dividing $p^2 - p + 1$. Because $p^2 - p + 1$ divides the order $p^6 - 1$ of $\text{GF}(p^6)^*$ this g can be thought of as a generator of an order q subgroup of $\text{GF}(p^6)^*$. As shown in [6], since $p^2 - p + 1$ does not divide any $p^s - 1$ for any integer s smaller than and dividing 6, the subgroup generated by g cannot be embedded in the multiplicative group of any true subfield of $\text{GF}(p^6)$ (assuming q is sufficiently large). We show, however, that arbitrary powers of g can be represented using a single element of the subfield $\text{GF}(p^2)$, that such powers can be computed using arithmetic operations in $\text{GF}(p^2)$, and that arithmetic in the extension field $\text{GF}(p^6)$ can be avoided. Moreover, our exponentiation method is much more efficient than other published methods to compute powers of elements of order dividing $p^2 - p + 1$.

In Section 2 we describe our method to represent and calculate powers of subgroup elements. In Section 3 we explain how a proper subgroup generator can conveniently be found using the method from Section 2. Cryptographic applications are given in Section 4, along with comparisons with RSA and ECC. In Section 5 we prove

that the security of our method is equivalent to the security offered by traditional subgroup approaches. Extensions of our method are discussed in Section 6.

2. Subgroup representation and arithmetic

2.1 System setup

Let $p \equiv 2 \pmod{3}$ be a prime number such that $6\log_2(p) \approx 1024$ and such that $\phi_6(p) = p^2 - p + 1$ has a prime factor q with $\log_2(q) \geq 160$. Such p and q (or of any other reasonable desired size) can quickly be found by picking a prime $q \equiv 7 \pmod{12}$, by finding the two roots r_1 and r_2 of $x^2 - x + 1 \equiv 0 \pmod{q}$, and by finding an integer k such that $r_i + k*q$ is $2 \pmod{3}$ and prime for $i = 1$ or 2 . If desired, primes q can be selected until the smallest or the largest root is prime, or any other straightforward variant that fits one's needs may be used, for instance to get $\log_2(q) \approx 180$ and $6\log_2(p) \approx 3000$, i.e., $\log_2(p)$ considerably bigger than $\log_2(q)$. From $q \equiv 7 \pmod{12}$ it follows that $q \equiv 1 \pmod{3}$ so that, with quadratic reciprocity, $x^2 - x + 1 \equiv 0 \pmod{q}$ has two roots. It also follows that $q \equiv 3 \pmod{4}$ which implies that those roots can be found using a single $((q+1)/4)^{\text{th}}$ powering modulo q .

By $g \in \text{GF}(p^6)$ we denote an element of order q . It is well known that g is not contained in any proper subfield of $\text{GF}(p^6)$ (cf. [4]). In the next section it is shown that there no need for an actual representation of g and that arithmetic on elements of $\text{GF}(p^6)$ can be entirely avoided. Thus, there is no need to represent elements of $\text{GF}(p^6)$, for instance by constructing an irreducible 3rd degree polynomial over $\text{GF}(p^2)$. A representation of $\text{GF}(p^2)$ is needed however. This is done as follows.

From $p \equiv 2 \pmod{3}$ it follows that $p \pmod{3}$ generates $\text{GF}(3)^*$, so that the zeros α and α^p of the polynomial $(X^3 - 1)/(X - 1) = X^2 + X + 1$ form an optimal normal basis for $\text{GF}(p^2)$ over $\text{GF}(p)$. Because $\alpha^i = \alpha^{i \bmod 3}$, an element $x \in \text{GF}(p^2)$ can be represented as $x_0\alpha + x_1\alpha^p = x_0\alpha + x_1\alpha^2$ for $x_0, x_1 \in \text{GF}(p)$, so that $x^p = x_0^p\alpha^p + x_1^p\alpha^{2p} = x_1\alpha + x_0\alpha^2$.

Figure 5 is a flow diagram of the method for selection of "p", as shown in section 2.1.

2.2 Cost of arithmetic in $\text{GF}(p^2)$

It follows from the last identity that p^{th} powering is for free in $\text{GF}(p^2)$. A squaring in $\text{GF}(p^2)$ can be carried out at the cost of 2 squarings and a single multiplication in $\text{GF}(p)$,

where as customary we do not count additions in $\text{GF}(p)$. Straightforward multiplication in $\text{GF}(p^2)$ takes four multiplications in $\text{GF}(p)$, but this can trivially be reduced to three by using a simple Karatsuba-like approach (cf. [5, section 4.3.3]): to compute $(x_0\alpha + x_1\alpha^2) * (y_0\alpha + y_1\alpha^2)$ it suffices to compute $x_0 * y_0$, $x_1 * y_1$, and $(x_0 + x_1) * (y_0 + y_1)$, after which $x_0 * y_1 + x_1 * y_0$ follows using two subtractions.

2.3 Compact representation of powers of g and their conjugates

We present a number of straightforward results that show that powers of g , up to conjugacy, can be represented using a single element of $\text{GF}(p^2)$.

We recall the definition of the trace function $\text{Tr}(x)$ from $\text{GF}(p^6)$ onto $\text{GF}(p^2)$ mapping x to $x + x^{p^2} + x^{p^4}$. Because the order of $x \in \text{GF}(p^6)^*$ divides $p^6 - 1$ the function is well defined. For $x, y \in \text{GF}(p^6)$ and $c \in \text{GF}(p^2)$, $\text{Tr}(x+y) = \text{Tr}(x) + \text{Tr}(y)$ and $\text{Tr}(cx) = c * \text{Tr}(x)$. That is, $\text{Tr}(x)$ is $\text{GF}(p^2)$ -linear.

Lemma 2.3.1. *The minimal polynomial of g over $\text{GF}(p^2)$ is $X^3 - BX^2 + B^p X - 1 \in \text{GF}(p^2)[X]$ with $B = g + g^{p-1} + g^{-p} \in \text{GF}(p^2)$.*

Proof. Because g is not contained in any proper subfield of $\text{GF}(p^6)$ it is a root of a unique monic irreducible polynomial $F(X) = X^3 - BX^2 + CX - D \in \text{GF}(p^2)[X]$. Because $F(X)^{p^2} = F(X^{p^2})$ the roots of $F(X)$ are g and its conjugates g^{p^2} and g^{p^4} . Because the order q of g divides $p^2 - p + 1$ and because $p^2 \equiv p - 1 \pmod{p^2 - p + 1}$ and $p^4 \equiv -p \pmod{p^2 - p + 1}$, we find that $g^{p^2} = g^{p-1}$ and $g^{p^4} = g^{-p}$ so that

$$D = g * g^{p^2} * g^{p^4} = g * g^{p-1} * g^{-p} = g^{1+p-1-p} = 1$$

and

$$B = g + g^{p^2} + g^{p^4} = g + g^{p-1} + g^{-p}.$$

Note that $B = \text{Tr}(g)$. From $F(g^{-p}) = 0$ it follows that

$$\begin{aligned} g^{-3p} - Bg^{-2p} + Cg^{-p} - 1 &= g^{-3p}(1 - Bg^p + Cg^{2p} - g^{3p}) = \\ g^{-3p}(1 - B^{1/p}g + C^{1/p}g^2 - g^3)^p &= 0. \end{aligned}$$

Because $F(X)$ is the unique monic irreducible polynomial in $\text{GF}(p^2)[X]$ that has g as a root it follows that $B = C^{1/p}$, i.e., $C = B^p$, which finishes the proof.

Remark 2.3.2. The identity $C = B^p$ in the proof of Lemma 2.3.1 also follows from

$$C = g * g^{p-1} + g * g^{-p} + g^{p-1} * g^{-p} = g^p + g^{1-p} + g^{-1}$$

and

$$B^p = (g + g^{p-1} + g^{-p})^p = g^p + g^{-1} + g^{1-p}$$

since $p^2 - p \equiv -1 \pmod{p^2 - p + 1}$ and $-p^2 \equiv 1 - p \pmod{p^2 - p + 1}$.

Based on Lemma 2.3.1 it is tempting to represent g and its conjugates by $\text{Tr}(g)$. We show that a result similar to Lemma 2.3.1 holds for any power of g and its conjugates. Consequently, g^n and its conjugates can be represented by $\text{Tr}(g^n)$. For notational convenience we use the following definition.

Definition 2.3.3. Let $T(n) = \text{Tr}(g^n) \in \text{GF}(p^2)$. Note that $T(n) = g^n + g^{np-n} + g^{-np}$ and that $T(1) = B$ with B as in Lemma 2.3.1.

Lemma 2.3.4. $T(np) = T(n)^p = g^{-n} + g^{n-np} + g^{np} = T(-n)$.

Proof. Immediate from the definition of $T(n)$ and from

$$g^{np} + g^{np^2-np} + g^{-np^2} = g^{-n} + g^{n-np} + g^{np} = T(-n)$$

as in Remark 2.3.2.

Lemma 2.3.5. For any integer n the roots of the polynomial $X^3 - T(n)X^2 + T(n)^p X - 1 \in \text{GF}(p^2)[X]$ are g^n and its conjugates $g^{np^2} = g^{np-n}$ and $g^{np^4} = g^{-np}$.

Proof. We compare the coefficients with the coefficients of the polynomial $(X - g)(X - g^{np-n})(X - g^{-np})$. The coefficient of X^2 follows from Definition 2.3.3, the constant coefficient from $g^{n+np-n-np} = 1$, and the coefficient of X from

$$g^{n+np-n} + g^{n-np} + g^{np-n-np} = g^{np} + g^{n-np} + g^{-n}$$

and Lemma 2.3.4.

2.4 Computing $T(n)$ for arbitrary n

We show that $T(n)$ can efficiently be computed for any non-negative integer n .

Lemma 2.4.1. $T(u+v) = T(u) * T(v) - T(v)^p * T(u-v) + T(u-2v)$.

Proof. Immediate from the definition of $T(u)$ and $T(v)^p = T(-v)$ (cf. Lemma 2.3.4).

Corollary 2.4.2. Let $B = T(1)$ as in Lemma 2.3.1.

- i. $T(2n) = T(n)^2 - 2T(n)^p;$
- ii. $T(n+1) = B * T(n) - B^p * T(n-1) + T(n-2);$
- iii. $T(2n-1) = T(n) * T(n-1) - B * T(n-1)^p + T(n-2)^p.$
- iv. $T(2n-3) = T(n-2) * T(n-1) - B^p * T(n-1)^p + T(n)^p.$

Proof.

- i. This follows from Lemma 2.4.1 with $u = v = n$, $T(0) = 3$, and Lemma 2.3.4:

$$T(2n) = T(n)^2 - T(n)^p * T(0) + T(-n) = T(n)^2 - 3T(n)^p + T(n)^p = T(n)^2 - 2T(n)^p.$$
- ii. This follows from Lemma 2.4.1 with $u = n$ and $v = 1$.
- iii. This follows from Lemma 2.4.1 with $u = n$, $v = n-1$ and Lemma 2.3.4.
- iv. This follows from Lemma 2.4.1 with $u = n-2$, $v = n-1$ and Lemma 2.3.4.

Definition 2.4.3. Let $S(n) = (T(n-2), T(n-1), T(n))$ for $n > 0$, where $T(-1) = T(1)^p = B^p$ (cf. Lemma 2.3.4) and $T(0) = 3$.

Algorithm 2.4.4 for the computation of $T(n)$ given $B = T(1)$. Given B (and B^p), we show how $S(n+1)$ and $S(2n)$ can be computed based on $S(n)$. Computation of $T(n)$ for arbitrary n then follows using the ordinary square and multiply method based on $S(1) = (B^p, 3, B)$ (cf. Definition 2.4.3).

- $S(n+1)$ can be computed from $S(n)$ using Corollary 2.4.2.ii. This takes two multiplications in $\text{GF}(p^2)$.
- $S(2n)$ can be computed by first using Corollary 2.4.2.i to compute $T(2n-2)$ and $T(2n)$ given $S(n)$, at the cost of two squarings in $\text{GF}(p^2)$, followed by an application of Corollary 2.4.2.iii to compute $T(2n-1)$ at the cost of two multiplications in $\text{GF}(p^2)$.

In both steps we use that p th powering is for free in $\text{GF}(p^2)$. Figure 6 is a flow diagram of the arithmetic method to support key generation, as shown in section 2.4.4.

Theorem 2.4.5. Let $w(n)$ denote the number of ones in the binary expansion of n . The representation $T(n)$ of the n th power of g and its conjugates can be computed at the cost of $2*\log_2(n)$ squarings in $\text{GF}(p^2)$ and $2*w(n) + 2*\log_2(n)$ multiplications in $\text{GF}(p^2)$.

Proof. Immediate from Algorithm 2.4.4.

Corollary 2.4.6. *With $w(n)$ as in Theorem 2.4.5, the representation $T(n)$ of the n th power of g and its conjugates can be computed at the cost of $4*\log_2(n)$ squarings and $6*w(n)+8*\log_2(n)$ multiplications in $\text{GF}(p)$.*

Proof. Immediate from Theorem 2.4.5 and 2.2.

Remark 2.4.7. Assuming that $w(n) \approx (\log_2(n)/2)$ and that a squaring in $\text{GF}(p)$ takes 80% of the time of a multiplication in $\text{GF}(p)$, we find that the computation of $T(n)$ for $n \approx q$ can be performed at an expected cost of about $14.2*\log_2(q)$ multiplications in $\text{GF}(p)$. This is more than 60% faster than the $37.8*\log_2(q)$ multiplications in $\text{GF}(p)$ required by the method from [4] where powers of g are more traditionally represented as elements of $\text{GF}(p^6)$ and which is substantially faster than standard methods to deal with subgroups. For the last estimate we assume that $\log_2(q) \approx \log_2(p)$. If elements of $\langle g \rangle$ are represented using a 3rd degree extension of $\text{GF}(p^2)$, then exponentiation would take $42.3*\log_2(q)$ multiplications in $\text{GF}(p)$, due to the fact that arithmetic in $\text{GF}(p^2)$ is fast and because an extension polynomial of the special form $X^3 - BX^2 + B^p X - 1$ may be used. Note that, unlike the methods from for instance [1], we do not assume that p has a special form. Using such primes leads to additional savings by making the arithmetic in $\text{GF}(p)$ faster.

Corollary 2.4.2.iv allows us to replace the standard square and multiply method by the less well known binary method, thereby saving some multiplications.

Algorithm 2.4.8 for the computation of $T(n)$ given $B = T(1)$. Given B and $S(n)$ it is straightforward to compute $S(2n)$ or $S(2n-1)$ using Corollary 2.4.2:

- $S(2n)$ is computed as in Algorithm 2.4.4 at the cost of two squarings and two multiplications in $\text{GF}(p^2)$.
- $S(2n-1)$ is computed by computing $T(2n-1)$ and $T(2n-2)$ as above at the cost of one squaring and two multiplications in $\text{GF}(p^2)$, and by computing $T(2n-3)$ using Corollary 2.4.2.iv at the cost of two multiplications in $\text{GF}(p^2)$.

In both steps we use that p th powering is for free in $\text{GF}(p^2)$.

Let $n > 2$ be some odd positive integer. To compute $T(n)$ we proceed as follows. Let $S(2) = (3, B, B^2 - 2B^p)$ (cf. Definition 2.4.3 and Corollary 2.4.2.i), let r be such that $2^r < n < 2^{r+1}$, let $2^{r+1} - n = \sum_{0 \leq i < r} n_i 2^i$ with $n_i \in \{0,1\}$, and let $k = 2$. For $i = r-1, r-2, \dots, 0$ in

succession replace $S(k)$ by $S(2k)$ and k by $2k$ if $n_i = 0$ and $S(k)$ by $S(2k-1)$ and k by $2k-1$ if $n_i = 1$. As a result we have that $k = n$ so that $T(n)$ follows from $S(n)$.

If n is even we apply the above procedure to the odd part of n followed by one or more applications of Corollary 2.4.2.i.

Theorem 2.4.9. *For a randomly selected N -bit number n , the representation $T(n)$ of the n th power of g and its conjugates can be computed at an expected cost of $1.5*N$ squarings and $3*N$ multiplications in $\text{GF}(p^2)$.*

Proof. Immediate from Algorithm 2.4.8.

Corollary 2.4.10. *For a randomly selected N -bit number n , the representation $T(n)$ of the n th power of g and its conjugates can be computed at an expected cost of $3*N$ squarings and $9.5*N$ multiplications in $\text{GF}(p)$.*

Proof. Application of Theorem 2.4.9 and 2.2 leads to $3*N$ squarings and $10.5*N$ multiplications in $\text{GF}(p)$. In the computation of $S(2n-1)$, however, we compute both $B * T(n-1)^p$ and $B^p * T(n-1)^p$, which can be done using 4 as opposed to 6 multiplications in $\text{GF}(p)$ if we combine the computations. So we may expect to be able to save a total of $(2*N)/2$ multiplications in $\text{GF}(p)$.

Remark 2.4.11. We find that the computation of $T(n)$ for $n \approx q$ can be performed at an expected cost of about $11.9 * \log_2(q)$ multiplications in $\text{GF}(p)$ (cf. assumptions in Remark 2.4.7). Thus, Algorithm 2.4.8 can be expected to be more than 15% faster than Algorithm 2.4.4. Under the assumption that $\log_2(q) \approx \log_2(p)$, exponentiation using Algorithm 2.4.8 is more than 3 times faster than the fast method from [4] mentioned in 2.4.7.

2.5 Computing powers of products

Efficient representation and computation of powers of g suffices for the implementation of many cryptographic protocols. Sometimes, however, the product of two powers of g must be computed. For the standard representations this is straightforward, but in our representation computing products is relatively complicated. Here we sketch how the problem of computing the product of two powers of g may be solved. Our description is geared towards cryptographic applications, but can easily be generalized. Let B represent

a generator g of a subgroup of order q dividing $p^2 - p + 1$, as in Lemma 2.3.1. Let $y = g^k$ for a secret integer k (the private key), and let $C = y + y^{p-1} + y^{-p}$ be y 's representation. Obviously, the owner of the private key k can easily arrange the computation of C such that the representations C_+ of $g*y = g^{k+1}$ and C_- of $y/g = g^{k-1}$ are computed as well. We show that if B , C , C_+ , and C_- are known, then for any pair of integers a , b the representation of $g^a * y^b$ and its conjugates can be computed efficiently.

Lemma 2.5.1. *Let $T(m)$ be the representation of g^m and its conjugates, and let A be the*

following 3×3 -dimensional matrix over $\text{GF}(p^2)$: $A = \begin{pmatrix} B & -B^p & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$. Then

$$\begin{pmatrix} T(n+1) \\ T(n) \\ T(n-1) \end{pmatrix} = A^n * \begin{pmatrix} T(1) \\ T(0) \\ T(-1) \end{pmatrix}, \text{ where } T(1) = B, T(0) = 3, \text{ and } T(-1) = B^p \text{ (cf. 2.3.3 and 2.3.4).}$$

Proof. From the definition of A and $T(n+1) = B * T(n) - B^p * T(n-1) + T(n-2)$ (cf.

Corollary 2.4.2.ii) it follows that $\begin{pmatrix} T(n+1) \\ T(n) \\ T(n-1) \end{pmatrix} = A * \begin{pmatrix} T(n) \\ T(n-1) \\ T(n-2) \end{pmatrix}$. The proof follows by induction.

Thus, if for the representations $T(u)$ and $T(v)$ of g^u and g^v the u th and v th powers of A are known, then the representation $T(u+v)$ of g^{u+v} can simply be computed by applying Lemma 2.5.1 with $n = u + v$ to $A^{u+v} = A^u * A^v$. We show how A^u can be obtained from $T(u)$, if $T(u+1)$ and $T(u-1)$ are known as well.

Lemma 2.5.2. *Given $T(0)$, $T(1)$, $T(-1)$, $T(n)$, $T(n+1)$, and $T(n-1)$ the matrix A^n can be*

computed as $A^n = \begin{pmatrix} T(n) & T(n+1)T(n+2) \\ T(n-1) & T(n) & T(n+1) \\ T(n-2)T(n-1) & T(n) \end{pmatrix} \begin{pmatrix} T(0) & T(1) & T(2) \\ T(-1) & T(0) & T(1) \\ T(-2)T(-1)T(0) \end{pmatrix}^{-1}$ in a small constant number of operations in $\text{GF}(p^2)$.

Proof. Given $T(0)$, $T(1)$, $T(-1)$, $T(n)$, $T(n+1)$, and $T(n-1)$, Corollary 2.4.2.ii is used to compute $T(\pm 2)$ and $T(n \pm 2)$. As in the proof of Lemma 2.5.1 it follows that

$\begin{pmatrix} T(n) & T(n+1)T(n+2) \\ T(n-1) & T(n) & T(n+1) \\ T(n-2)T(n-1) & T(n) \end{pmatrix} = A^n * \begin{pmatrix} T(0) & T(1) & T(2) \\ T(-1) & T(0) & T(1) \\ T(-2)T(-1)T(0) \end{pmatrix}$. The proof follows by observing

that $\begin{pmatrix} T(-2)T(-1)T(0) \\ T(-1) & T(0) & T(1) \\ T(0) & T(1) & T(2) \end{pmatrix}$ is the product of the Vandermonde matrix $\begin{pmatrix} g^{-1} & g^{-p^2} & g^{-p^4} \\ 1 & 1 & 1 \\ g & g^{p^2} & g^{p^4} \end{pmatrix}$

and its transpose, and therefore invertible. The determinant of the latter matrix equals $T(p+1)^p - T(p+1)$, and $(T(p+1)^p - T(p+1))^2 = B^{2p+2} + 18*B^{p+1} - 4*(B^{3p} + B^3) - 27 \in GF(p)$. Because p^{th} powering is for free in $GF(p^2)$, the proof follows.

Algorithm 2.5.3 for the computation of the representation of $g^a * y^b$ for integers a, b with $1 < a, b < q$, given the representation B of g and the representations C, C_+ , and C_- of $y, y*g$, and y/g , respectively.

1. Compute $c = a/b \bmod q$;
2. Given B use Algorithm 2.4.8 to compute $T(c+1), T(c), T(c-1)$ (note that the final applications of Corollary 2.4.2.i in Algorithm 2.4.8, if any, should be replaced by the usual calculation of the full $S(2n)$);
3. Use Lemma 2.5.2 with $T(0) = 3, T(1) = B, T(-1) = B^p, T(c), T(c+1)$, and $T(c-1)$ to compute A^c ;
4. Use Lemma 2.5.2 with $T(0) = 3, T(1) = B, T(-1) = B^p, T(k) = C, T(c+1) = C_+$, and $T(c-1) = C_-$ to compute the corresponding power of A , which we denote by A^k , even though k is unknown;
5. Compute A^{c+k} ;
6. Using Lemma 2.5.1 and A^{c+k} compute $T(c+k)$;
7. Use Algorithm 2.4.8 with B replaced by $T(c+k)$ and n replaced by b to compute the representation $T((c+k)*b) = T(a+k*b)$ of $g^a * y^b$.

Figure 10A is a flow diagram of the arithmetic method to support generating digital signatures, as shown in section 2.5.3.

Theorem 2.5.4. *For randomly selected N-bit numbers a and b , the representation of $g^a * y^b$ and its conjugates can be computed at an expected cost of $3*N$ squarings and $6*N$ multiplications in $GF(p^2)$ plus a small constant number of 3×3 matrix multiplications over $GF(p^2)$.*

Proof. Immediate from Algorithm 2.5.3 and Theorem 2.4.9.

Corollary 2.5.5. *For randomly selected N-bit numbers a and b , the representation of $g^a * y^b$ and its conjugates can be computed at an expected cost of $6*N$ squarings and $19*N$ multiplications in $\text{GF}(p)$ plus a small constant number of 3×3 matrix multiplications over $\text{GF}(p^2)$.*

Proof. Immediate from Algorithm 2.5.3, Corollary 2.4.10, and 2.2.

Remark 2.5.6. Under the second assumption made in Remark 2.4.7, we find that the computation of the representation of $g^a * y^b$ for $a \approx b \approx q$ can be performed at an expected cost of about $23.8 * \log_2(q)$ multiplications in $\text{GF}(p)$. If the more traditional but fast method from [4] is used to represent $\text{GF}(p^6)$, then computation of the representation of $g^a * y^b$ takes almost $47 * \log_2(q)$ multiplications in $\text{GF}(p)$. If elements of $\langle g \rangle$ are represented using a 3rd degree extension of $\text{GF}(p^2)$ (cf. Remark 2.4.7), then the computation of the representation of $g^a * y^b$ takes about $51 * \log_2(q)$ multiplications in $\text{GF}(p)$. We conclude that both single and double exponentiations can be done much faster using our representation than using previously published techniques.

3. Fast initialization

We describe three different ways to compute a proper initial B as in Lemma 2.3.1, i.e., an element B of $\text{GF}(p^2)$ such that there is a $g \in \text{GF}(p^6)$ of order q dividing $p^2 - p + 1$ with $B = g + g^{p-1} + g^{-p}$.

3.1 Straightforward approach

Algorithm 3.1.1 for the computation of B .

1. Pick at random a third degree monic irreducible polynomial over $\text{GF}(p^2)$, and use that polynomial for representation of and arithmetic on elements of $\text{GF}(p^6)$.
2. Pick at random an element $h \in \text{GF}(p^6)^*$;
3. Compute the $((p^6 - 1)/q)$ th power g of h ;
4. If $g = 1$, then return to Step 2;

5. Compute $B = g + g^{p-1} + g^{-p}$.

Theorem 3.1.2. *Algorithm 3.1.1 can be expected to require 3 irreducibility tests over $\text{GF}(p^2)$ of third degree monic polynomials in $\text{GF}(p^2)[X]$, and $1-1/q$ exponentiations in $\text{GF}(p^6)^*$ with exponent $(p^6-1)/q$.*

Proof. Immediate from the well known fact that a random monic third degree polynomial in $\text{GF}(p^2)[X]$ is irreducible with probability $1/3$.

Although conceptually easy, Algorithm 3.1.1 requires actual representation of and manipulation with elements of $\text{GF}(p^6)$. From an implementation point of view it is therefore less attractive. Note that a random third degree polynomial $H(X)$ in $\text{GF}(p^2)[X]$ can be tested for irreducibility by testing if $\gcd(X^{p^2} - X, H(X)) = 1$ in $\text{GF}(p^2)[X]$. This requires about $2*\log_2(p)$ squarings and $\log_2(p)$ multiplications of elements of $\text{GF}(p^2)[X]/(H(X))$, which can be carried out in $12*\log_2(p)$ squarings and $69*\log_2(p)$ multiplications in $\text{GF}(p)$.

3.2 Randomized approach using irreducibility

Algorithm 3.2.1 for the computation of B .

1. Pick at random an element $B' \in \text{GF}(p^2)^* \setminus \text{GF}(p)^*$;
2. If $X^3 - B'X^2 + B'^p X - 1 \in \text{GF}(p^2)[X]$ is reducible, then return to Step 1;
3. Use Algorithm 2.4.8 with B replaced by B' to compute $T((p^2-p+1)/q)$ (i.e., with $B' = T(1)$) ;
4. If $T((p^2-p+1)/q) = 3$, then return to Step 1;
5. Let $B = T((p^2-p+1)/q)$.

To justify Algorithm 3.2.1 we use the following two lemmas.

Lemma 3.2.2. *An irreducible polynomial of the form $X^3 - B'X^2 + B'^p X - 1 \in \text{GF}(p^2)[X]$ is the minimal polynomial of an element of $\text{GF}(p^6)$ of order > 3 and dividing p^2-p+1 .*

Lemma 3.2.3. *For a randomly selected $B' \in \text{GF}(p^2)^* \setminus \text{GF}(p)^*$ the probability that the polynomial $X^3 - B'X^2 + B'^p X - 1 \in \text{GF}(p^2)[X]$ is irreducible is about one third.*

Lemma 3.2.2 proves that it makes sense to apply Algorithm 2.4.8 with B replaced by B' , because the role of g in Section 2 is played by some (unknown) element of $\text{GF}(p^6)$ of order dividing p^2-p+1 . This works because g never explicitly occurs in the computations in Algorithm 2.4.8 (except to compute B , which is replaced by B' for our current purposes).

Lemma 3.2.3 proves that on average only about three different values for B' have to be selected before an irreducible polynomial is found. The proof of the following theorem is immediate.

Theorem 3.2.4. *Algorithm 3.2.1 can be expected to require $3*(1-1/q)$ irreducibility tests over $\text{GF}(p^2)$ of third degree monic polynomials of the form $X^3 - B'X^2 + B'^p X - 1$ in $\text{GF}(p^2)[X]$, and $1-1/q$ applications of Algorithm 2.4.8 with $n = (p^2-p+1)/q$.*

Proof of Lemma 3.2.2. Because $X^3 - B'X^2 + B'^p X - 1 \in \text{GF}(p^2)[X]$ is irreducible its roots are in $\text{GF}(p^6)^* \setminus \text{GF}(p^2)^*$ and thus of order dividing $(p^6-1)/(p^2-1) = p^4+p^2+1$. Denote the roots by h and its conjugates h^{p^2} and $h^{p^4} = h^{-p^2-1}$, the latter because the order of h divides p^4+p^2+1 . If $h^3 = 1$, then h^{p^2} would be equal to h since $p \equiv 2 \pmod{3}$, and h would be in $\text{GF}(p^2)$ contradicting the irreducibility. Because the order of h cannot be even, it follows that the order of h is > 3 . Reversing the argument in the proof of Lemma 2.3.1 it follows that if h is a root, then so is h^{-p} . Thus either $h = h^{-p}$, or $h^{p^2} = h^{-p}$, or $h^{-p^2-1} = h^{-p}$. The first two possibilities are in contradiction with the fact that the order of h divides p^4+p^2+1 , that $\gcd(p^4+p^2+1, p+1) = 3$, and that the order of h is > 3 , and the last remaining possibility leads to the conclusion that the order of h divides p^2-p+1 .

Proof of Lemma 3.2.3. This follows from a straightforward counting argument. About p^2-p elements of the subgroup of order p^2-p+1 of $\text{GF}(p^6)^*$ are roots of monic irreducible polynomials of the form $X^3 - B'X^2 + B'^p X - 1 \in \text{GF}(p^2)[X]$ (cf. Lemma 2.3.1). Since each of these polynomials has three distinct roots, there must be about $(p^2-p)/3$ different values for B' in $\text{GF}(p^2)^* \setminus \text{GF}(p)^*$ such that $X^3 - B'X^2 + B'^p X - 1$ is irreducible.

Compared to Algorithm 3.1.1, the arithmetic in $\text{GF}(p^6)$ is replaced in Algorithm 3.2.1 by application of Algorithm 2.4.8. That is much more convenient for the implementation of our method, because Algorithm 2.4.8 is required anyhow. We now show that the irreducibility tests can be replaced by an application of Algorithm 2.4.8 as well.

3.3 Randomized approach without irreducibility

If B' as in Step 1 of Algorithm 3.2.1 leads to an irreducible polynomial in Step 2, then we know that $T(n)$ corresponds to the sum of the conjugates of the n th powers of an element of order dividing p^2-p+1 and we know how to compute $T(n)$ efficiently based on B' . We now consider what we can say about a thus computed $T(n)$ if the polynomial in Step 2 of Algorithm 3.2.1 is not known to be irreducible. This leads to results that are very similar to those of Section 2, but the proofs are slightly more cumbersome.

Let B' be an element of $\text{GF}(p^2)$ and let α, β , and γ be the, not necessarily distinct, roots of $F(X) = X^3 - B'X^2 + B'^p X - 1 \in \text{GF}(p^2)[X]$.

Lemma 3.3.1.

- i. $B' = \alpha + \beta + \gamma$;
- ii. $\alpha * \beta * \gamma = 1$;
- iii. $\alpha^n * \beta^n + \alpha^n * \gamma^n + \beta^n * \gamma^n = \gamma^{-n} + \beta^{-n} + \alpha^{-n}$ for any integer n .

Proof. Immediate. Note that iii uses ii.

If $F(X)$ is irreducible, then it follows from Lemma 3.2.2 that α, β , and γ are of the form g, g^{p-1}, g^{-p} for some g in $\text{GF}(p^6)$ of order > 3 and dividing p^2-p+1 . If $F(X)$ is reducible, we have the following lemma.

Lemma 3.3.2. *If $F(X)$ is reducible, then α, β, γ are in $\text{GF}(p^2)$.*

Proof. Using the same argument as in the proof of Lemma 3.2.2 we find that α^{-p}, β^{-p} , and γ^{-p} are also roots of $F(X)$. Without loss of generality, we find that either $\alpha = \alpha^{-p}, \beta = \beta^{-p}, \gamma = \gamma^{-p}$, or $\alpha = \alpha^{-p}, \gamma = \beta^{-p}, \beta = \gamma^{-p}$, or $\beta = \alpha^{-p}, \gamma = \beta^{-p}, \alpha = \gamma^{-p}$. In the first case all roots have order divisible by $p+1$, so that they are all in $\text{GF}(p^2)$. In the second case α has order divisible by $p+1$ and β and γ have order divisible by p^2-1 , so that they are again all in $\text{GF}(p^2)$. In the final case it follows that $1 = \alpha * \beta * \gamma = \alpha * \alpha^{-p} * \alpha^{-p} = \alpha^{1-p+p^2} = \beta^{1-p+p^2} = \gamma^{1-p+p^2}$. Because $F(X)$ is reducible, at least one root, say α , is in $\text{GF}(p^2)$, so that the order of α divides $\text{gcd}(p^2-p+1, p^2-1) = 3$ (since $p \equiv 2 \pmod{3}$). But from $\alpha^3 = 1, \beta = \alpha^{-p}$, and $\gamma = \beta^{-p}$ it now follows that $\alpha = \beta = \gamma = \alpha^{-p}$ so that the third case does not occur but is covered by the first case.

Definition 3.3.3. Let $V(n) = \alpha^n + \beta^n + \gamma^n$. Note that $V(1) = B'$ and that $V(n) \in GF(p^2)$ because $V(n) = T(n)$ if $F(X)$ is irreducible and $\alpha, \beta, \gamma \in GF(p^2)$ otherwise.

Lemma 3.3.4. $V(np) = V(n)^p = \alpha^{-n} + \beta^{-n} + \gamma^{-n} = V(-n)$.

Proof. From the proof of Lemma 3.3.2 it follows that $\alpha + \beta + \gamma = \alpha^{-p} + \beta^{-p} + \gamma^{-p}$ and, more generally, that $\alpha^m + \beta^m + \gamma^m = \alpha^{-mp} + \beta^{-mp} + \gamma^{-mp}$ for any integer m . The proof follows by taking $m = -n$.

Lemma 3.3.5. For any integer n the roots of the polynomial $X^3 - V(n)X^2 + V(n)^p X - 1 \in GF(p^2)[X]$ are α^n, β^n , and γ^n .

Proof. If $F(X)$ is irreducible the result follows from Lemma 2.3.5, so let us assume that $F(X)$ is reducible. As in the proof of Lemma 2.3.5 we compare the coefficients with the coefficients of the polynomial $(X - \alpha^n)(X - \beta^n)(X - \gamma^n)$. The coefficient of X^2 follows from Definition 3.3.3, the constant coefficient from Lemma 3.3.1.ii, and the coefficient of X from Lemma 3.3.1.iii and Lemma 3.3.4.

It follows from Lemmas 2.3.5 and 3.3.5 that even if $F(X)$ is reducible, $V(n)$ and $T(n)$ play very similar roles, because they can be used in the same way to define a polynomial that has the n th powers of the roots of $F(X)$ as its roots. We now show that $V(n)$ can be computed in the same way as $T(n)$.

Lemma 3.3.6. $V(u+v) = V(u) * V(v) - V(v)^p * V(u-v) + V(u-2v)$.

Proof. Immediate from the definition of $V(u)$ and $V(v)^p = V(-v)$ (cf. Lemma 3.3.4).

Algorithms 2.4.4 and 2.4.8 are based on Corollary 2.4.2, which is based on Lemma 2.4.1. Lemma 3.3.6 is the equivalent of Lemma 2.4.1 with T replaced by V . Therefore, $V(n)$ can be computed using Algorithm 2.4.4 or Algorithm 2.4.8 with B replaced by B' and T replaced by V .

Lemma 3.3.7. $F(X) \in GF(p^2)[X]$ is reducible if and only if $V(p+1) \in GF(p)$.

Proof. If $F(X)$ is reducible then $\alpha, \beta, \gamma \in GF(p^2)$ (Lemma 3.3.2) so that $\alpha^{p+1}, \beta^{p+1}, \gamma^{p+1} \in GF(p)$ and thus $V(p+1) = \alpha^{p+1} + \beta^{p+1} + \gamma^{p+1} \in GF(p)$. If $V(p+1) \in GF(p)$, then $V(p+1)^p$

$= V(p+1)$, so that $X^3 - V(p+1)X^2 + V(p+1)X - 1$ has 1 as a root. Because the roots of $X^3 - V(p+1)X^2 + V(p+1)X - 1$ are the $(p+1)$ st powers of the roots of $F(X)$ (cf. Lemma 3.3.5), it follows that $F(X)$ has a root of order dividing $p+1$, so that $F(X)$ is reducible over $\text{GF}(p^2)$.

This leads to the following algorithm to find a proper initial B as in Lemma 2.3.1.

Algorithm 3.3.8 for the computation of B .

1. Pick at random an element $B' \in \text{GF}(p^2)^* \setminus \text{GF}(p)^*$;
2. Use Algorithm 2.4.8 with B replaced by B' and T replaced by V to compute $V(p+1)$ (i.e., with $B' = T(1) = V(1)$);
3. If $V(p+1) \in \text{GF}(p)$, then return to Step 1;
4. Use Algorithm 2.4.8 with B replaced by B' to compute $T((p^2-p+1)/q)$ (i.e., with $B' = T(1)$);
5. If $T((p^2-p+1)/q) = 3$, then return to Step 1;
6. Let $B = T((p^2-p+1)/q)$.

Figure 7 is a flow diagram of the method of key generation, as shown in section 3.3.8.

Theorem 3.3.9. *Algorithm 3.3.8 computes an element $B \in \text{GF}(p^2)$ such that $B = g + g^{p-1} + g^{-p}$ for an element g of $\text{GF}(p^6)$ of order $q > 3$ dividing $p^2 - p + 1$. It can be expected to require $3*(1-1/q)$ applications of Algorithm 2.4.8 with $n = p+1$ and $1-1/q$ applications of Algorithm 2.4.8 with $n = (p^2-p+1)/q$.*

Proof. The correctness of Algorithm 3.3.8 follows from the fact that $F(X)$ is irreducible if $V(p+1) \notin \text{GF}(p)$ (Lemma 3.3.7). The run time estimate follows from Lemma 3.2.3 and the fact that $V(p+1) \notin \text{GF}(p)$ if $F(X)$ is irreducible (Lemma 3.3.7).

4. Applications

The subgroup representation method described in Section 2 can be used in any cryptosystem that relies on the (subgroup) discrete logarithm problem. In this section we describe some of these applications in more detail. We assume that primes p and q have been selected as described in 2.1 such that q divides $p^2 - p + 1$ and that $B \in \text{GF}(p^2)$ has

been determined as representation of a generator of a subgroup of order q , for instance using the method described in Section 3. We also discuss how the public key data p , q , and B may be represented, and we compare the performance of our method with RSA and ECC.

4.1 Application to the Diffie-Hellman scheme

Suppose that two parties, Alice and Bob, who both have access to the public key data p , q , B want to agree on a shared secret key. They can do this by performing the following variant of the Diffie-Hellman scheme:

1. Alice selects at random an integer a , $1 < a < q - 2$, uses Algorithm 2.4.8 to compute $V_A = T(a) \in GF(p^2)$, and sends V_A to Bob.
2. Bob receives V_A from Alice, selects at random an integer b , $1 < b < q - 2$, uses Algorithm 2.4.8 to compute $V_B = T(b) \in GF(p^2)$, and sends V_B to Alice.
3. Alice receives V_B from Bob, and uses Algorithm 2.4.8 with B replaced by V_B (i.e., with $V_B = T(1)$) to compute $K_{AB} = T(a) \in GF(p^2)$.
4. Bob uses Algorithm 2.4.8 with B replaced by V_A (i.e., with $V_A = T(1)$) to compute $K_{AB} = T(b) \in GF(p^2)$.

The length of the messages exchanged in this DH variant is about one third of the length of the messages in other implementations of the DH scheme that achieve the same level of security and that are based on the difficulty of computing discrete logarithms in (a subgroup of) the multiplicative group of a finite field. Also, our variant of the DH scheme requires considerable less computation than those previously published methods (cf. Remark 2.4.11).

Figure 8 is a flow diagram of the method of Diffie Hellman key exchange, as shown in section 4.1, using keys generated by the method of Figure 7.

4.2 Application to the ElGamal encryption scheme

Suppose that Alice is the owner of the public key data p , q , B , and that Alice has selected a secret integer k and computed the corresponding public value $C = T(k)$ using Algorithm 2.4.8. Thus, Alice's public key data consists of (p, q, B, C) . Given Alice's public key (p, q, B, C) Bob can encrypt a message M intended for Alice using the following variant of ElGamal encryption:

1. Bob selects at random an integer b , $1 < b < q - 2$;
2. Bob uses Algorithm 2.4.8 to compute $V_B = T(b) \in GF(p^2)$;

3. Bob uses Algorithm 2.4.8 with B replaced by C (i.e., with $C = T(1)$) to compute $K = T(b) \in GF(p^2)$;
4. Bob uses K to encrypt M , resulting in the encryption E .
5. Bob sends (V_B, E) to Alice.

Note that Bob may have to hash the bits representing K down to a suitable encryption key length.

Upon receipt of (V_B, E) , Alice decrypts the message in the following manner:

1. Alice uses Algorithm 2.4.8 with B replaced by V_B (i.e., with $V_B = T(1)$) to compute $K = T(k) \in GF(p^2)$;
2. Alice uses K to decrypt E resulting in M .

The message (V_B, E) sent by Bob consists of the actual encryption E , whose length strongly depends on the length of M , and the overhead V_B , whose length is independent of the length of M . The length of the overhead in this variant of the ElGamal encryption scheme is about one third of the length of the overhead in other implementations of message-length independent ElGamal encryption (cf. Remark 4.2.1). Also, our method is considerably faster (cf. Remark 2.4.11). Figure 9 is a flow diagram of the method of ElGamal encryption, as shown in section 4.2, using keys generated by the method of Figure 7.

Remark 4.2.1. Our variant of ElGamal encryption is based on the common message-length independent version of ElGamal encryption, i.e., where the key K is used in conjunction with an (unspecified) symmetric key encryption method. In more traditional ElGamal encryption the message is restricted to the key space and ‘encrypted’ using, for instance, multiplication by the key, an invertible operation that takes place in the key space. In our description this would amount to requiring that $M \in GF(p^2)$, and by computing E as $K*M \in GF(p^2)$. Compared to this more traditional variant of ElGamal encryption we save a factor three on the length of both parts of the encrypted message, for messages that fit in our key space (of one third of the ‘traditional’ size).

4.3 Application to digital signature schemes

Let, as in 4.2, Alice’s public key data consists of (p, q, B, C) , where $C = T(k)$ and k is Alice’s private key. Furthermore, assume that $C_+ = T(k+1)$ and $C_- = T(k-1)$ are included in Alice’s public key (cf. 2.5). We show how the Nyberg-Rueppel (NR) message recovery signature scheme can be implemented using our subgroup representation. Application of our method to other digital signature schemes goes in a similar way. To

sign a message M containing an agreed upon type of redundancy, Alice does the following:

1. Alice selects at random an integer a , $1 < a < q - 2$;
2. Alice uses Algorithm 2.4.8 to compute $V_A = T(a) \in \text{GF}(p^2)$;
3. Alice uses V_A to encrypt M , resulting in the encryption E .
4. Alice computes the (integer valued) hash h of E .
5. Alice computes $s = (k * h + a)$ modulo q in the range $\{0, 1, \dots, q-1\}$.
6. Alice's resulting signature on M is (E, s) .

As in 4.2 Alice may have to hash the bits representing V_A down to a suitable encryption key length.

To verify Alice's signature (E, s) and to recover the signed message M , Bob does the following:

1. Bob obtains Alice public key data (p, q, B, C, C_+, C_-) .
2. Bob checks that $0 \leq s < q$; if not failure.
3. Bob computes the hash h of E (using the same hash function used by Alice).
4. Bob replaces h by $-h$ modulo q (i.e., in the range $\{0, 1, \dots, q-1\}$).
5. Bob uses Algorithm 2.5.3 to compute the representation V_B of $g^s * y^h$ given $a = s$, $b = h, B, C, C_+$, and C_- .
6. Bob uses V_B to decrypt E resulting in the message M .
7. If M contains the agreed upon type of redundancy, then the signature is accepted; if not the signature is rejected.

Both for signature generation and signature verification our method is considerably faster than other subgroup based implementations of the NR scheme (cf. Remarks 2.4.11 and 2.5.6). The length of the signature is identical to other variants of the NR scheme that are message-length independent (cf. Remark 4.2.1): an overhead part of length depending on the desired security (i.e, the subgroup size) and a message part of length depending on the message itself and the agreed upon redundancy. Similar statements hold for other digital signature schemes, such as DSA.

Figure 10B is a flow diagram of the method of generating digital signatures, as shown in section 4.3., using keys generated by the method of Figure 7.

4.4 Public key size

For the applications in 4.1 and 4.2 a public key consisting of (p, q, B, C) suffices. For the digital signature application in 4.3 a much larger public key consisting of (p, q, B, C, C_+, C_-) is required. We assume that public keys are certified in some way, and that the

certificates contain information identifying the owner of the key. Furthermore, we assume that the bit-lengths P of p and Q of q are fixed system parameters, known to all parties in the system, and that $P > Q - 2$ (cf. 2.1). We discuss how much overhead is required for the representation of the public key in a certificate, i.e., on top of the user ID and other certification related bits.

If no attempts are made to compress the key, then representing (p, q, B, C) takes $5*P + Q$ bits, and (p, q, B, C, C_+, C_-) requires $9*P + Q$ bits. We sketch one possible way how, at the cost of a small computational overhead for the recipient of the public key, p , q , and B can be represented using far fewer than $3*P + Q$ bits.

First of all, the prime q can be determined as a function f of the user ID and a small seed s , for some function f that is known to all parties in the system. The seed could consist of a random part s_1 and a small additive part s_2 that is computed by the party that determines q , for instance by finding a small integer s_2 (of about $\log_2(Q)$ bits) such that $12*(f(\text{ID}, s_1) + s_2) + 7$ is prime (and defines q , cf. 2.1). Given q , the smallest (or largest) root r in $\{0, 1, \dots, q-1\}$ of $x^2 - x + 1$ modulo q can be found using a single exponentiation in $\text{GF}(q)$. From P an integer z_1 easily follows such that p should be at least $r + z_1*q$, and a small integer z_2 (of about $\log_2(P)$ bits) can be found such that $r + z_1*q + z_2*q$ is prime (and defines p , cf. 2.1). Thus, assuming that f , P , and Q are system-wide parameters, the primes q and p can be determined given the user ID, s , and z_2 at the cost of essentially a single exponentiation in $\text{GF}(q)$. Alternatively, and if allowed by P , the party determining q may pick random s_1 's until r (or $r + z_1*q$) itself is prime (and defines p). In that case q and p are fully determined by and can quickly be recovered from the user ID and s .

To compress the number of bits required for the representation of B we assume that the party that determines B uses Algorithm 3.3.8, but instead of selecting B' at random in Step 1 of Algorithm 3.3.8, tries $B' = i\alpha + (i+1)\alpha^2$ (cf. 2.1) for $i = 2, 3, 4, \dots$, in succession, until Step 6 is reached. The final B' can usually be represented using at most 5 bits (if not, just pick another s_1 and start all over again). The corresponding B can be determined given B' at the cost of a single application of Algorithm 2.4.8 with B replaced by B' , as in Step 4 of Algorithm 3.3.8.

All these computations to recover p , q , and B can easily be performed by the recipient of a certificate. Correctness of the bits provided (i.e., if they lead to primes q and p of the right sizes, and to a B representing an order q element) should be verified by the certification authority. We conclude that p , q , and B can be selected in such a way that they can be recovered from the user ID and an additional $\log_2(s_1) + \log_2(Q) + \log_2(P) + 5$ bits. In practical situations 48 additional bits, i.e., 6 bytes, should be enough.

We conclude that for our versions of the DH scheme and ElGamal encryption the public key data overhead in the certificates can be limited to $48 + 2*P$ bits: 48 bits from which p , q , and B can be derived, and $2*P$ bits for C . For 170-bit subgroups and 1024-bit finite fields that is about one third of the size of traditional subgroup public keys. It is somewhat more than twice the size of an ECC public key, assuming the finite field, elliptic curve data, and group size are shared among all parties in the ECC system. If curves or finite fields are not shared, then ECC public keys need substantially more bits than our method when applied as in 4.1 or 4.2 unless similar ID based methods are used for curve and finite field generation (cf. 4.5).

The public key overhead of our method when used in conjunction with digital signatures, as in 4.3, is much larger, namely $48 + 6*P$ bits. This is still competitive with traditional subgroup public key sizes, but more than non-shared ECC public key sizes. In the next subsection we show how $2*P$ bits can be saved at the cost of a moderate one time computation for the recipient of the public key.

4.5 Reducing the public key size for digital signature applications

For digital signature applications of our method the public key contains C , C_+ , and C_- . We show that, at the cost of a moderate one time computation for the recipient of the public key, it suffices to send just two of C , C_+ , and C_- , thereby reducing the public key overhead for digital signature applications of our method from $48 + 6*P$ to approximately $48 + 4*P$ bits. An easy way to see this is as follows. Assume that C and C_+ are given. From Lemma 2.5.2 with $T(0) = 3$, $T(1) = B$, $T(n) = C$ and $T(n+1) = C_+$ and the fact that the determinant of the matrix A equals 1 it follows that $T(n-1) = C_-$ has to be determined such that the determinant of the matrix from Lemma 2.5.2 with $T(n)$ on the diagonal equals the determinant of the matrix from Lemma 2.5.2 with $T(0)$ on the diagonal. This leads to a third degree equation in $T(n-1)$ (i.e., C_-) over $\text{GF}(p^2)$, which can be solved at the cost of a small number of p^{th} powerings in $\text{GF}(p^2)$. The correct candidate can be determined at the cost of at most a few additional bits in the public key. We present a conceptually more complicated method that can be used not only to determine C_- , but that can also be used to establish the correctness of C_+ (i.e., that C_+ is the proper value corresponding to B and C). Let $C = y + y^{p-1} + y^{-p}$, as in 2.5.

Definition 4.5.1. Let $F_r \in \text{GF}(p^2)[X]$ denote the minimal polynomial over $\text{GF}(p^2)$ of $r \in \text{GF}(p^6)$.

Definition 4.5.2. Let $r, s \in \text{GF}(p^6)$. The root-product $\mathfrak{R}(r,s)$ of r and s is defined as the polynomial with roots $\{\alpha * \beta \mid \alpha, \beta \in \text{GF}(p^6), F_r(\alpha) = 0, F_s(\beta) = 0\}$.

Lemma 4.5.3. Let $r, s \in \text{GF}(p^6)$. Then $\mathfrak{R}(r,s) = F_{rs} * F_{rs^{p^2}} * F_{rs^{p^4}} \in \text{GF}(p^2)[X]$.

Proof. According to Definition 4.5.2 the roots of the root-product $\mathfrak{R}(r,s)$ are $r^{p^i}s^{p^j}$ for $i, j \in \{0, 2, 4\}$, i.e., rs and its conjugates over $\text{GF}(p^2)$ (for $i=j$), rs^{p^2} and its conjugates (for $j \equiv i+2 \pmod{6}$), and rs^{p^4} and its conjugates (for $j \equiv i+4 \pmod{6}$). The proof follows.

Lemma 4.5.4. Given B and $T(p-2)$, values $K, L, M \in \text{GF}(p^2)$ such that $g^p \equiv Kg^2 + Lg + M$ modulo $g^3 - Bg^2 + B^pg - 1$ can be computed at the cost of a small constant number of operations in $\text{GF}(p^2)$.

Proof. By raising $g^p \equiv Kg^2 + Lg + M$ to the $(p^i)^{\text{th}}$ power for $i = 0, 2, 4$, and by adding the three resulting identities, we find that $T(p) = KT(2) + LT(1) + MT(0)$. Similarly, from $g^{p-1} \equiv Kg + L + Mg^{-1}$ and $g^{p-2} \equiv K + Lg^{-1} + Mg^{-2}$ it follows that $T(p-1) = KT(1) + LT(0) + MT(-1)$ and $T(p-2) = KT(0) + LT(-1) + MT(-2)$, respectively. With $T(p-1) = T(p^2) = T(1) = B$ and $T(p) = T(1)^p = B^p$, this leads to the following system of equations over $\text{GF}(p^2)$:

$$\begin{pmatrix} T(p-2) \\ B \\ B^p \end{pmatrix} = \begin{pmatrix} T(0) & T(1) & T(2) \\ T(-1) & T(0) & T(1) \\ T(-2) & T(-1) & T(0) \end{pmatrix} \begin{pmatrix} K \\ L \\ M \end{pmatrix}.$$

Because $T(p-2)$ is given and the matrix on the right hand side is invertible (cf. proof of Lemma 2.5.2) the proof follows.

Lemma 4.5.5. Given B, C , and $T(p-2)$, the root-product $\mathfrak{R}(g, y)$ can be computed at the cost of a small constant number of operations in $\text{GF}(p^2)$.

Proof. Since $C = y + y^{p-1} + y^{-p}$ we have that $F_y(X) = X^3 - CX^2 + C^pX - 1 \in \text{GF}(p^2)[X]$. For any $z \in \text{GF}(p^6)$ the roots of the polynomial $z^3 * F_y(X/z) \in \text{GF}(p^6)[X]$ are zy, zy^{p-1}, zy^{-p} . Thus, $\mathfrak{R}(g, y) \in \text{GF}(p^2)[X]$ can be written as the following product in $\text{GF}(p^6)[X]$:

$$(g^3 * F_y(X * g^{-1})) * (g^{3(p-1)} * F_y(X * g^{-p+1})) * (g^{-3p} * F_y(X * g^p)) =$$

$$F_y(X*g^{-1}) * F_y(X*g^{-p+1}) * F_y(X*g^p),$$

because the product of g and its conjugates equals 1. To compute $\mathfrak{R}(g, y)$ we represent $\text{GF}(p^6)$ as $\text{GF}(p^2)[X]/F_g(X) = \text{GF}(p^2)(g)$, i.e., by adjoining g with $g^3 - Bg^2 + B^pg - 1 = 0$ to $\text{GF}(p^2)$. In this representation, $F_y(X*g^{-1})$ can easily be computed. The remaining two factors $F_y(X*g^{-p+1})$ and $F_y(X*g^p)$ can be computed given a representation of g^p in $\text{GF}(p^2)(g)$, i.e., $K, L, M \in \text{GF}(p^2)$ such that $g^p = Kg^2 + Lg + M$. With Lemma 4.5.4 the proof now follows.

Lemma 4.5.6. *Given B , C , C_+ , and $T(p-2)$, the correctness of C_+ can be checked at the cost of a small constant number of operations in $\text{GF}(p^2)$.*

Proof. Given B and C , the value for C_+ is correct if the roots in $\text{GF}(p^6)$ of the polynomial $X^3 - C_+X^2 + C_+^pX - 1 \in \text{GF}(p^2)[X]$ are $\alpha\beta$ and their conjugates, where α is a root of $X^3 - BX^2 + B^pX - 1$ (i.e., $\alpha = g, g^{p-1}$, or g^{-p}) and β is a root of $X^3 - CX^2 + C^pX - 1$ (i.e., $\beta = y, y^{p-1}$, or y^{-p}). According to Lemma 4.5.3 the root-product $\mathfrak{R}(g,y) \in \text{GF}(p^2)[X]$ is the product of the three minimal polynomials of gy , gy^{p-1} , and gy^{-p} , respectively, so that C_+ is correct if and only if the polynomial $X^3 - C_+X^2 + C_+^pX - 1 \in \text{GF}(p^2)[X]$ divides $\mathfrak{R}(g,y)$. The proof now follows from Lemma 4.5.5.

Lemma 4.5.7. *Given B , C , C_+ , and $T(p-2)$, the corresponding C_- can be computed at the cost of a small constant number of operations in $\text{GF}(p^2)$.*

Proof. Without loss of generality we assume that the roots of $X^3 - C_+X^2 + C_+^pX - 1$ are gy and its conjugates. It follows from Lemma 4.5.3 that the corresponding C_- satisfies $X^3 - C_-X^2 + C_-^pX - 1 = \gcd(\mathfrak{R}(g^{-1},y), \mathfrak{R}(g^{-2},gy))$. The proof now follows from the observation that the root-products $\mathfrak{R}(g^{-1},y)$ and $\mathfrak{R}(g^{-2},gy)$ can be computed as in the proof of Lemma 4.5.5 (with C replaced by C_+ for the computation of $\mathfrak{R}(g^{-2},gy)$).

Lemma 4.5.8. *Given B , the value of $T(p-2)$ can be computed at the cost of a squareroot computation in $\text{GF}(p)$, assuming one bit of information to resolve the squareroot ambiguity.*

Proof. It follows from Corollary 2.4.2.ii, $T(p) = B^p$, and $T(p-1) = T(1) = B$ that $T(p-2) = T(p+1)$. Let $T(p+1) = x_1\alpha + x_2\alpha^2$ with $x_1, x_2 \in \text{GF}(p)$. Thus, $-(x_1 + x_2) = T(p+1)^p + T(p+1)$ (cf. 2.1). With $T(p+1) = g^{p+1} + g^{p-2} + g^{-2p+1}$, $T(p+1)^p = g^{-p-1} + g^{-p+2} + g^{2p-1}$, and $B^{p+1} =$

$$\begin{aligned} B*B^p &= (g + g^{p-1} + g^{-p})*(g^p + g^{-1} + g^{-p+1}) = g^{p+1} + g^{p-2} + g^{-2p+1} + g^{-p-1} + g^{-p+2} + g^{2p-1} + 3 \\ &= T(p+1)^p + T(p+1) + 3 \text{ it follows that } x_1 + x_2 = 3 - B^{p+1} \in GF(p). \end{aligned}$$

Similarly, it follows from straightforward evaluation that $(T(p+1)^p - T(p+1))^2 = -3*(x_1 - x_2)^2$. With the identity for $(T(p+1)^p - T(p+1))^2$ given in the proof of Lemma 2.5.2 we find that $-3*(x_1 - x_2)^2 = B^{2p+2} + 18*B^{p+1} - 4*(B^{3p} + B^3) - 27 \in GF(p)$. The proof follows by using that $x_1 + x_2 = 3 - B^{p+1}$.

It follows from Lemma 4.5.7 that C_- does not have to be included in the public key for digital signature applications. A single additional bit is required in the public key if Lemma 4.5.8 is used by the recipient of the public key to compute $T(p-2)$. The expected cost of the computation of $T(p-2)$ using Lemma 4.5.8 is $1.3*\log_2(p)$ multiplications in $GF(p)$ if we make the additional assumption that $p \equiv 3 \pmod{4}$. Without Lemma 4.5.8, and without the additional bit, the computation of $T(p-2)$ takes an expected $11.9*\log_2(p)$ multiplications in $GF(p)$, according to 2.4.11. Note that also C_+ does in principle not have to be included in the public key, because the recipient can determine C_+ by factoring the ninth degree polynomial $\mathfrak{R}(g,y) \in GF(p^2)[X]$ into three third degree irreducible polynomials in $GF(p^2)[X]$.

4.6 Comparison with RSA and ECC

We give a rough comparison of the performance of RSA, ECC, and our method, which we refer to as XTR. We assume that XTR with $P = Q = 170$ (cf. 4.4) offers approximately the same security as $6*P$ -bit RSA with a 32-bit public exponent and as ECC with a randomly selected curve over a random P -bit prime field and with a Q -bit prime dividing the group order.

4.6.1. Public key sizes. For all systems the number of bits of the public keys depends on the way the public keys are generated, because in all cases considerable savings can be obtained by including the user ID in the generation process (cf. 4.4). For RSA the user ID may be included in the modulus (cf. [7]) and the public exponent may be fixed or determined as a function of the used ID. As a consequence, the size of the RSA public key varies between $3*P$ and $6*P + 32$ bits, depending on whether ID based compression methods are used or not. If, in ECC, the curve and finite field information is shared, then the public key information consists of $P + 1$ bits for the public point, assuming its y -coordinate is represented by a single bit, irrespective of the inclusion of user ID information. In a non-shared ECC setup, the finite field, random curve, and group order

information take approximately $3.5*P$ bits, plus a small constant number of bits to represent a point of high order. Using a method similar to the one in 4.4 this can be reduced to an overhead (on top of the user ID) of, say, 48 bits (to generate the curve and finite field as a function of the user ID and 48 random bits) plus $P/2$ bits (for the group order information). Thus, non-shared ECC public key sizes vary between $49 + 1.5*P$ and $1 + 4.5*P$ bits. For XTR the public key size varies between $48 + 2*P$ and $5*P + Q$ bits if no digital signatures are required or $48 + 4*P$ and $7*P + Q$ otherwise, as described in 4.4 and 4.5.

ID based key generation methods for RSA affect the way the modulus and its secret factors are determined. The ID based approach for RSA is therefore viewed with suspicion and not generally used, despite the fact that no attacks on the methods from, for instance, [7] are known. For discrete logarithm based methods (such as ECC and XTR) ID based key generation methods affect only the part of the public key that is not related to the secret information, i.e., the way the public point is determined is not affected. The ID based approach is therefore commonly used for discrete logarithm based systems. This distinction between RSA on the one hand, and ECC and XTR on the other hand, should be kept in mind while interpreting the public key length data in Table 1.

4.6.2. Speed. In Table 1 speed is measured as approximate number of multiplications in a 170-bit field. RSA-encryption (or signature verification) with a 32-bit public exponent and a $6*P$ -bit field requires approximately 32 squarings and 16 multiplications in the field, which is assumed to be equivalent to approximately $0.8*32 + 16$ multiplications, and thus about 36 as many, i.e., about 1500, multiplications in a 170-bit field. The number of operations required for RSA-decryption (or signature generation) is twice approximately $3*P$ squarings and $1.5*P$ multiplications in a $3*P$ -bit field, which amounts to about 11900 multiplications in a 170-bit field. For the ECC estimates we use the optimized results from [3], both for the two separate scalar multiplications in ECC-ElGamal encryption, and for the single scalar multiplication in ECC-ElGamal decryption and ECC-NR signature generation. The two scalar multiplications in ECC-NR signature verification can be combined, but it is as yet unclear if the methods from [3] can be used for this purpose. For that reason we use the estimate 2575 based on a rather straightforward but reasonably fast implementation; it is conceivable that this can be improved to, approximately, 2125 using the methods from [3]. The XTR estimates are based on 4.2, Remark 2.4.11, 4.3, and Remark 2.5.6.

The speeds given in Table 1 should not be confused with actual run times. Relatively speaking, actual run times for ECC and XTR should be close to the figures in

Table 1. The performance of RSA may be somewhat better because in practical implementations a single 510-bit modular multiplication may be faster than nine 170-bit modular multiplications.

4.6.3. Signature and encryption size. For the encryption and digital signature sizes we assume a message consisting of m bits (including the redundancy) and, in 4.2, 4.3, and similar ECC applications, a symmetric encryption method using a 128-bit key. For RSA we assume that if the message is too long (to be encrypted or signed with message recovery using a single RSA application), then RSA is used in conjunction with the same symmetric encryption method.

4.6.4. Key generation. For RSA two independent $3P$ -bit primes have to be generated. For XTR either two independent P -bit primes (assuming z_2 as in 4.4 is allowed to be non-zero), or two dependent P -bit primes (assuming z_2 as in 4.4 is 0) have to be generated. In the former case XTR key generation may be expected to be about $3^4 = 81$ times faster than RSA key generation. In the latter case RSA and XTR key generation is about equally expensive for $P = 170$: on the order of $2*(3P)^4$ bit operations for RSA, and on the order of P^5 bit operations for XTR. ECC key generation is orders of magnitude slower and considerably more complicated than either RSA or XTR key generation.

Table 1

| | | RSA | ECC | | XTR (non-shared only) | |
|--------------------------------------|--------------|-----------------------------------|--|------------|-----------------------|--------------|
| Public key size | ID-based | | shared | non-shared | no signing | with signing |
| 510 | ID-based | 510 | 171 | 304 | 388 | 728 |
| | non ID-based | 1056 | 171 | 766 | 1020 | 1360 |
| Encryption speed | | 1500 | 3400 | | 4046 | |
| Decryption speed | | 11900 | 1700 | | 2023 | |
| Approximate encryption size | | $\max(1024, 128+m)$ | $171 + m$ | | $340 + m$ | |
| Digital signature generation speed | | 11900 | 1700 | | 2023 | |
| Digital signature verification speed | | 1500 | 2575 | | 4046 | |
| Approximate digital signature size | | $\max(1024, 128+m)$ | $170 + m$ | | $170 + m$ | |
| Key generation | | two independent 510-bit primes | curve with 170-bit prime order subgroup | | two 170-bit primes | |

5. Security

For completeness we sketch the straightforward proofs that traditional subgroup discrete logarithm and DH problems offer the same security as our versions. Let the notation be as in Section 2.

Lemma 5.1. *Given $y \in \langle g \rangle$, the discrete logarithm of y with respect to g can be found using a single call to an oracle that given a value $v \in \text{GF}(p^2)$ produces an integer a such that $T(a) = v$, if such an integer exists.*

Proof sketch. Let $y = g^b$ for some unknown integer b . Let a be the integer produced by an oracle call with $v = y + y^{p-1} + y^{-p} \in \text{GF}(p^2)$, then $a = b$, or $a \equiv b*(p-1) \pmod{p^2 - p + 1}$, or $a \equiv -b*p \pmod{p^2 - p + 1}$. Thus, b can be found by trying at most three different possibilities. □

Lemma 5.2. *Given $v \in \text{GF}(p^2)$ an integer a such that $T(a) = v$, if such an integer exists, can be found using a single call to an oracle that solves the discrete logarithm problem in $\langle g \rangle$.*

Proof sketch. Let $v \in \text{GF}(p^2)$. Determine the roots $\alpha, \beta, \gamma \in \text{GF}(p^6)$ of the polynomial $X^3 - vX^2 + v^pX - 1 \in \text{GF}(p^2)[X]$. If $\alpha, \beta, \gamma \notin \langle g \rangle$ (which can easily be checked), then a with $T(a) = v$ does not exist. Otherwise, assume without loss of generality that $\alpha \in \langle g \rangle$, and use the oracle to produce an integer a such that $g^a = \alpha$. This a satisfies $T(a) = v$.

Lemma 5.3. *Given g^a and g^b for unknown integers a and b , the value g^{ab} can be computed using two calls to an oracle that given $T(u)$ and $T(v)$, for unknown integers u, v , determines $T(uv)$.*

Proof sketch. Given g^a compute its conjugates $g^{a(p-1)}$ and g^{-ap} and $T(a) = g^a + g^{a(p-1)} + g^{-ap}$. Similarly, compute $T(b)$ and, using $g^a/g = g^{a-1}$, compute $T(a-1)$. Determine $T(ab)$ and $T((a-1)b)$ using two calls to the oracle. Determine the roots $\alpha, \beta, \gamma \in \text{GF}(p^6)$ of the polynomial $X^3 - T(ab)X^2 + T(ab)^pX - 1 \in \text{GF}(p^2)[X]$. We have that $\{\alpha, \beta, \gamma\} = \{g^{ab}, g^{ab(p-1)}, g^{-abp}\}$, but it is unclear which of α, β, γ is the value g^{ab} that we are looking for. For that reason we determine the roots $\alpha', \beta', \gamma' \in \text{GF}(p^6)$ of the polynomial $X^3 -$

$T((a-1)b)X^2 + T((a-1)b)^p X - 1 \in \text{GF}(p^2)[X]$. We have that $\{\alpha', \beta', \gamma'\} = \{g^{(a-1)b}, g^{(a-1)b(p-1)}, g^{-(a-1)bp}\}$, so that g^{ab} can be determined as $\{\alpha, \beta, \gamma\} \cap \{\alpha'*g^b, \beta'*g^b, \gamma'*g^b\}$.

Corollary 5.4. *Given g^a and g^b for unknown integers a and b , the value g^{ab} can be found with probability $\varepsilon/3$ using a single call to an oracle that given $T(u)$ and $T(v)$, for unknown integers u, v , determines $T(uv)$ with probability ε .*

Corollary 5.5. *Given g^a and g^b for unknown integers a and b , the value g^{ab} can be computed using a single call to an oracle that given $T(u)$ and $T(v)$, for unknown integers u, v , determines $T(uv)$, and at most two calls to an oracle that asserts the correctness of the resulting value g^{ab} .*

It follows from Corollary 5.5 that in many practical situations a single call to the $T(u), T(v) \rightarrow T(uv)$ oracle would suffice to find g^{ab} given g^a and g^b . As an example we mention DH key agreement where the resulting key is actually used after it has been established.

Lemma 5.6. *Given $T(u)$ and $T(v)$ for unknown integers u, v , the value $T(uv)$ can be found using a single call to an oracle that given g^a and g^b , for unknown integers a and b , determines g^{ab} .*

Proof sketch. Determine the roots $\alpha, \beta, \gamma \in \text{GF}(p^6)$ of the polynomial $X^3 - T(u)X^2 + T(u)^p X - 1 \in \text{GF}(p^2)[X]$ and the roots $\alpha', \beta', \gamma' \in \text{GF}(p^6)$ of the polynomial $X^3 - T(v)X^2 + T(v)^p X - 1 \in \text{GF}(p^2)[X]$. We have that $\alpha = g^{u(p-1)^i}$ and $\alpha' = g^{v(p-1)^j}$ for unknown $i, j \in \{0, 1, 2\}$. From α and α' determine $g^{uv(p-1)^{i+j}}$ using a single call to the oracle. Because the order of g divides $p^2 - p + 1$ the sum of $g^{uv(p-1)^{i+j}}$ and its conjugates equals $T(uv)$.

6. Extensions

Methods similar to the ones described in this paper can be used for compact representation of and fast arithmetic with elements of a subgroup of order dividing $p + 1$ in $\text{GF}(p^2)^*$, as used for instance in the public key system LUC (cf. [9]). For that application the savings obtained are smaller than in our application, and the resulting comparison to RSA and ECC is less favorable. For that reason we do not elaborate.

Instead of representing powers of g (and their conjugates) of order q dividing $\phi_6(p)$ by elements of $\text{GF}(p^2)$ as opposed to $\text{GF}(p^6)$, we can represent powers of elements of order dividing $\phi_{30}(p)$ by elements of $\text{GF}(p^{10})$ as opposed to $\text{GF}(p^{30})$ using the same methods as presented in sections 2 to 5. Because $10 + 1 = 11$ is prime (just as $2 + 1 = 3$ is prime) we can use an optimal normal basis to represent the underlying field $\text{GF}(p^{10})$, but the overall construction is more complicated and fewer suitable primes are available while no additional savings are obtained. The same holds for any integer x for which $2*x + 1$ is prime: powers of elements of order dividing $\phi_{6*x}(p)$ can be represented in $\text{GF}(p^{2*x})$ as opposed to $\text{GF}(p^{6*x})$, and the arithmetic with those powers in the field $\text{GF}(p^{2*x})$ is efficient. The case $x = 1$, as described in detail in this paper, is the most efficient and most flexible of this more general construction. For that reason we do not present the details of the more general construction.

We are not aware of constructions similar to the ones described in this paper that obtain more savings than obtained by our construction. We have reason to believe that such constructions do not exist, but at this point this is merely a conjecture for which reasonable evidence seems to exist (cf. [2]).

7. References

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Although illustrative embodiments of the present invention, and various modifications thereof, have been described in detail herein with reference to the accompanying drawings, it is to be understood that the invention is not limited to these precise embodiments and the described modifications, and that various changes and further modifications may be effected therein by one skilled in the art without departing from the scope or spirit of the invention as defined in the appended claims.

DRAFT - 0225-4188

CLAIMS

What is claimed is:

1. A method of determining a public key having a reduced length and a factor p, using $GF(p^2)$ arithmetic to achieve $GF(p^6)$ security, without explicitly constructing $GF(p^6)$, comprising the steps of:

selecting a number q and a number p such that $p^{**}2 - p + 1$ is an integer multiple of q;

selecting a number g of order q, where g and its conjugates can be represented by B, where $Fg(x) = x^{**}3 - Bx^{**}2 + (B^{**}p)x - 1$ and the roots are g, $g^{**}(p-1)$, $g^{**}(-p)$;

representing the powers of g using their trace over the field $GF(p^2)$;

selecting a private key; and

computing a public key as a function of g.

2. A method of encrypting a message using the public key generated by the method of claim 1.

3. A method of decrypting a message using the public and private key generated by the method of claim 1.

4. A method of signing a message using the public and private key generated by the method of claim 1.

5. A method of verifying a signature using the public key generated by the method of claim 1.

6. A method of Diffie Hellman key exchange and related schemes using the public key generated by the method of claim 1.

7. A system for determining a public key having a reduced length and a factor p, using $GF(p^2)$ arithmetic to achieve $GF(p^6)$ security, without explicitly constructing $GF(p^6)$, comprising:

a processor for selecting a number q and a number p such that $p^{**}2 - p + 1$ is an integer multiple of q;

said processor selecting a number g of order q, where g and its conjugates can be represented by B, where $Fg(x) = x^{**}3 - Bx^{**}2 + (B^{**}p)x - 1$ and the roots are g, $g^{**}(p-1)$, $g^{**}(-p)$;

said processor representing the powers of g using their trace over the field $GF(p^2)$;

said processor selecting a private key;

a memory coupled to said processor for storing the private key;

said processor computing a public key as a function of g; and

a network interface for distributing said public key over a network.

8. A system of encrypting a message using the public key generated by the system of claim 7.

9. A system of decrypting a message using the public and private key generated by the system of claim 7.

10. A system of signing a message using the public and private key generated by the system of claim 7.

11. A system of verifying a signature using the public key generated by the system of claim 7.

12. A system of Diffie Hellman key exchange and related schemes using the public key generated by the system of claim 7.

13. A computer program article of manufacture, comprising:

a computer readable medium for determining a public key having a reduced length and a factor p , using $GF(p^2)$ arithmetic to achieve $GF(p^6)$ security, without explicitly constructing $GF(p^6)$, comprising:

a computer program means in said computer readable medium, for selecting a number q and a number p such that $p^{**}2 - p + 1$ is an integer multiple of q ;

a computer program means in said computer readable medium, for selecting a number g of order q , where g and its conjugates can be represented by B , where $Fg(x) = x^{**}3 - Bx^{**}2 + (B^{**}p)x - 1$ and the roots are $g, g^{**}(p-1), g^{**}(-p)$;

a computer program means in said computer readable medium, for representing the powers of g using their trace over the field $GF(p^2)$;

a computer program means in said computer readable medium, for selecting a private key; and

a computer program means in said computer readable medium, for computing a public key as a function of g .

14. The article of manufacture of claim 13, which further comprises:

a computer program means in said computer readable medium, for encrypting a message using the public key.

15. The article of manufacture of claim 13, which further comprises:

a computer program means in said computer readable medium, for decrypting a message using the public and private key.

16. The article of manufacture of claim 13, which further comprises:
 - a computer program means in said computer readable medium, for signing a message using the public and private key.
17. The article of manufacture of claim 13, which further comprises:
 - a computer program means in said computer readable medium, for verifying a signature using the public key.
18. The article of manufacture of claim 13, which further comprises:
 - a computer program means in said computer readable medium, for Diffie Hellman key exchange and related schemes using the public key.

19. A business method of determining a public key having a reduced length and a factor p, using $GF(p^2)$ arithmetic to achieve $GF(p^6)$ security, without explicitly constructing $GF(p^6)$, comprising the steps of:
 - selecting a number q and a number p such that $p^{**}2 - p + 1$ is an integer multiple of q;
 - selecting a number g of order q, where g and its conjugates can be represented by B, where $Fg(x) = x^{**}3 - Bx^{**}2 + (B^{**}p)x - 1$ and the roots are g, $g^{**}(p-1)$, $g^{**}(-p)$;
 - representing the powers of g using their trace over the field $GF(p^2)$;
 - selecting a private key; and
 - computing a public key as a function of g.
20. A method of encrypting a message using the public key generated by the business method of claim 19.

21. The method of decrypting a message using the public and private key generated by the business method of claim 19.
22. The method of signing a message using the public and private key generated by the business method of claim 19.
23. The method of verifying a signature using the public key generated by the business method of claim 19.
24. The method of Diffie Hellman key exchange and related schemes using the public key generated by the business method of claim 19.

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ABSTRACT OF THE DISCLOSURE

Improvements are obtained in key generation and cryptographic applications in public key cryptography, by reducing the bit-length of public keys, thereby reducing the bandwidth requirements of telecommunications devices, such as wireless telephone sets.

FIG. 1

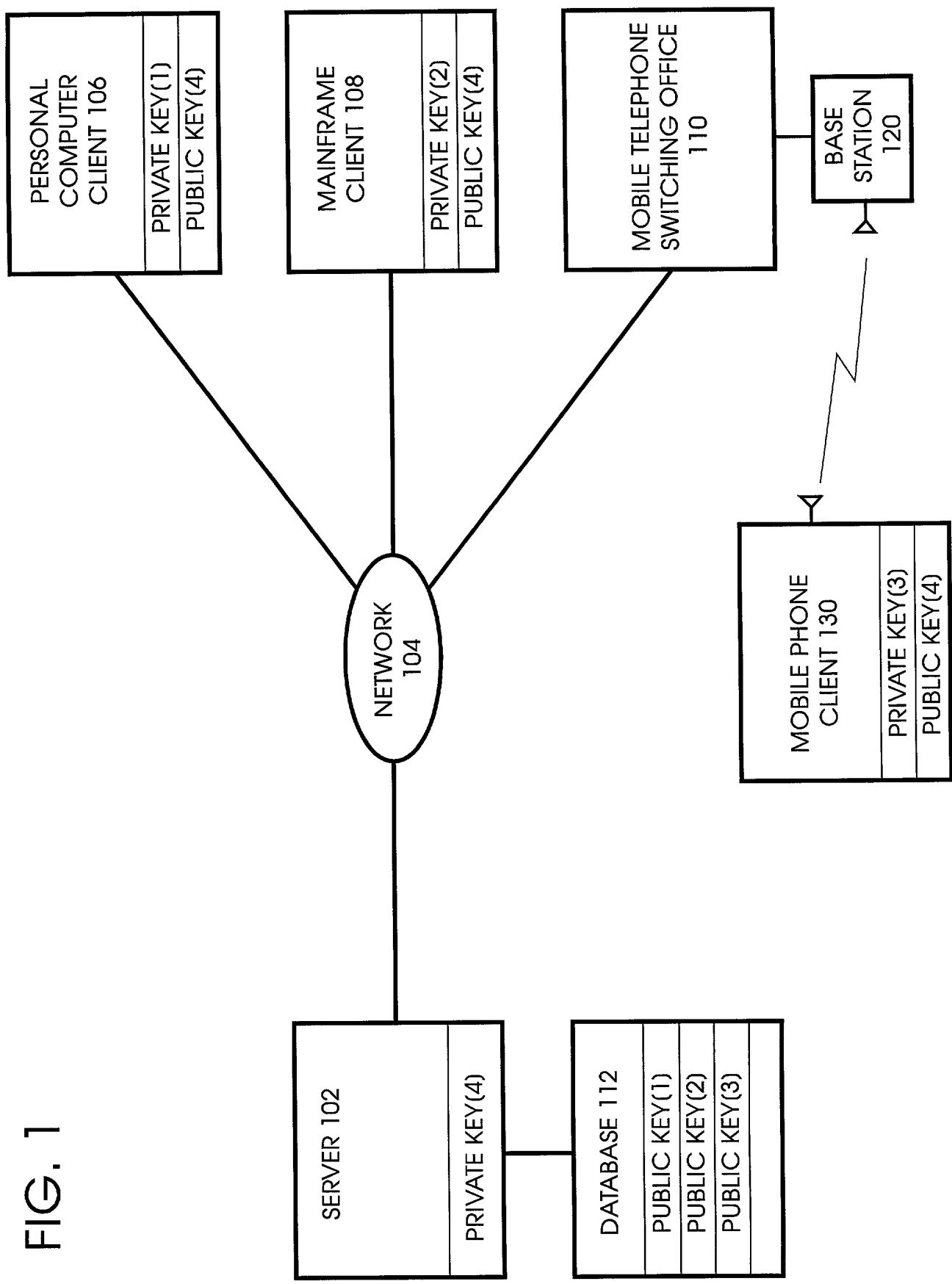


FIG. 2

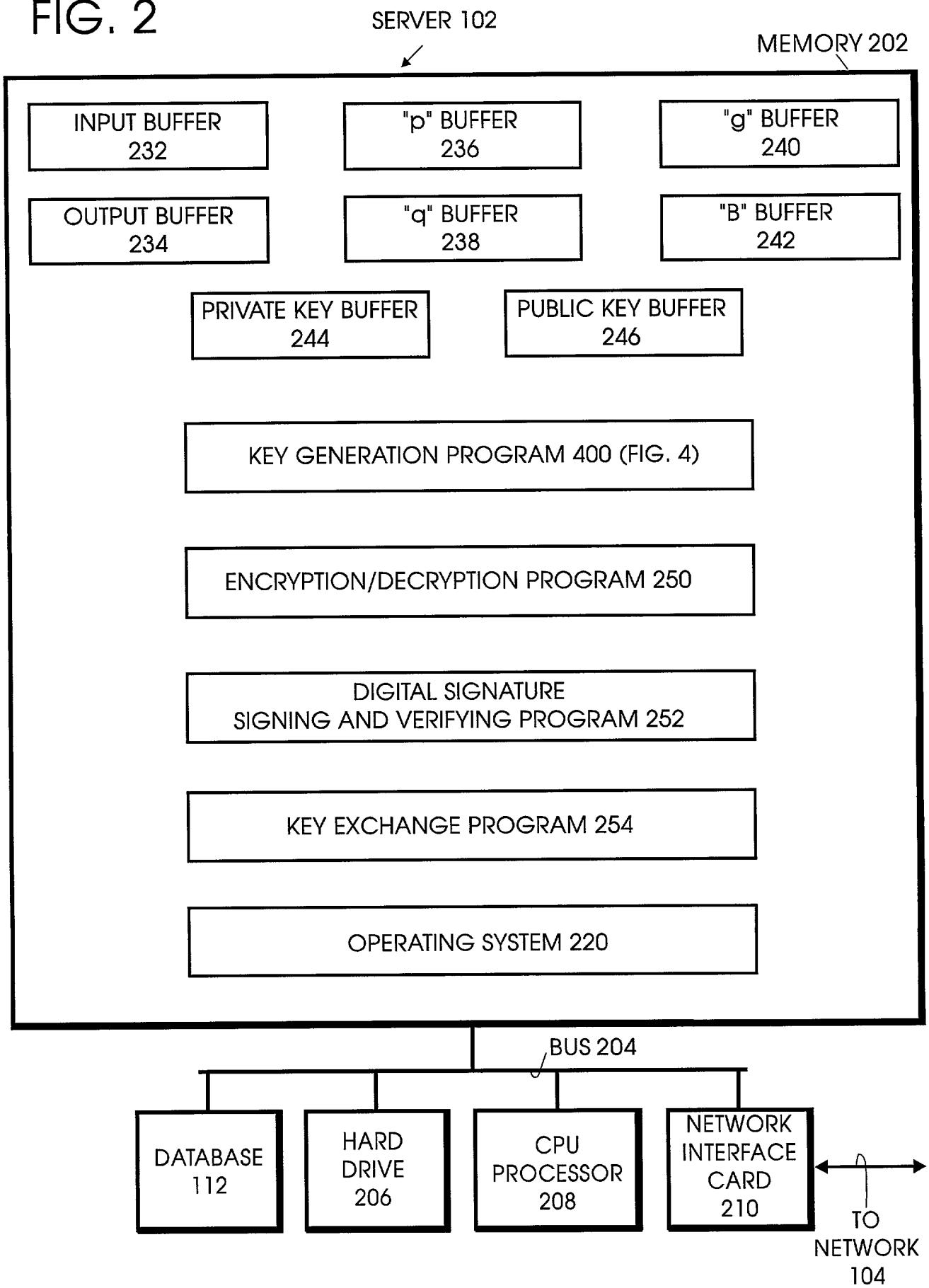


FIG. 3

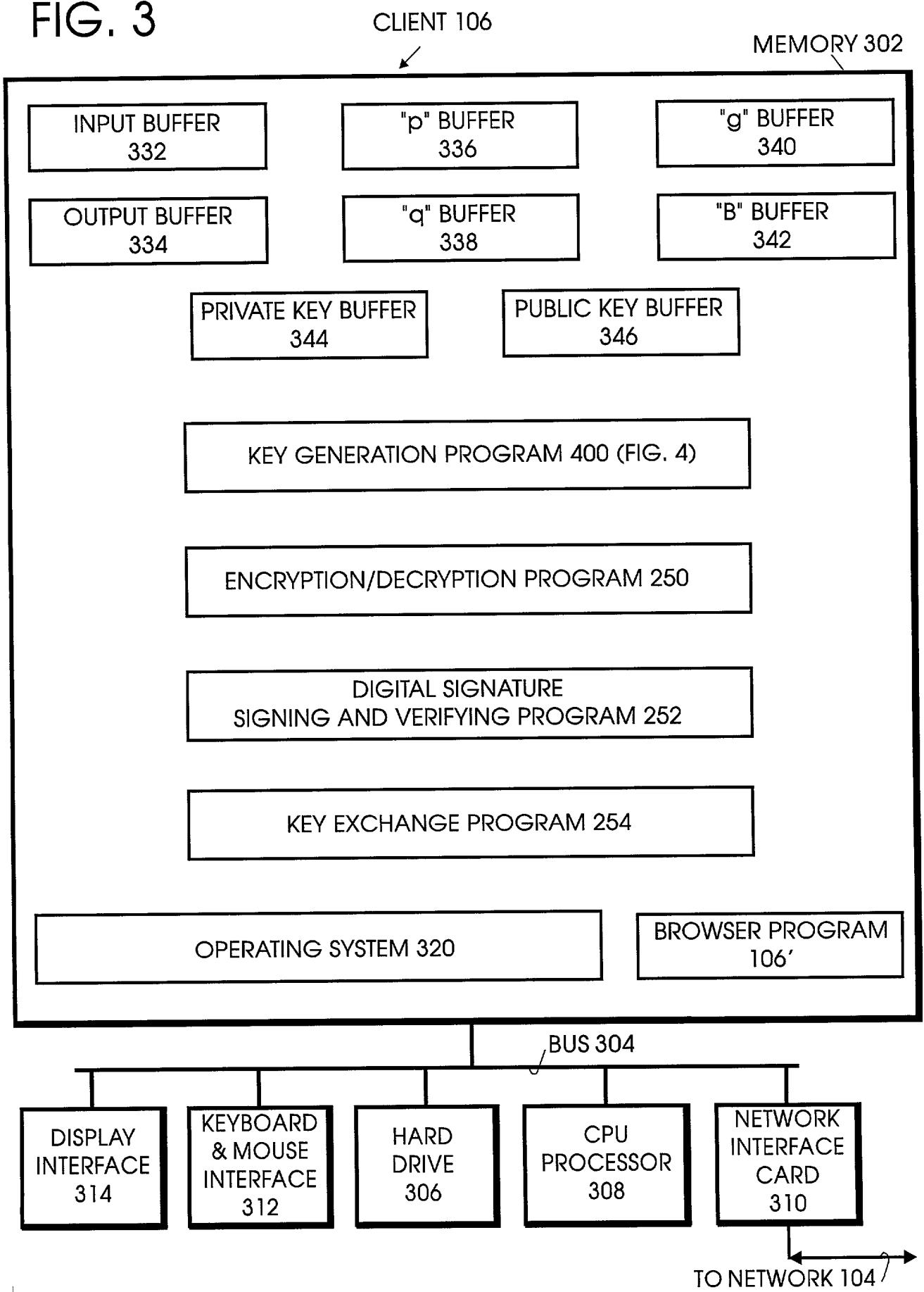
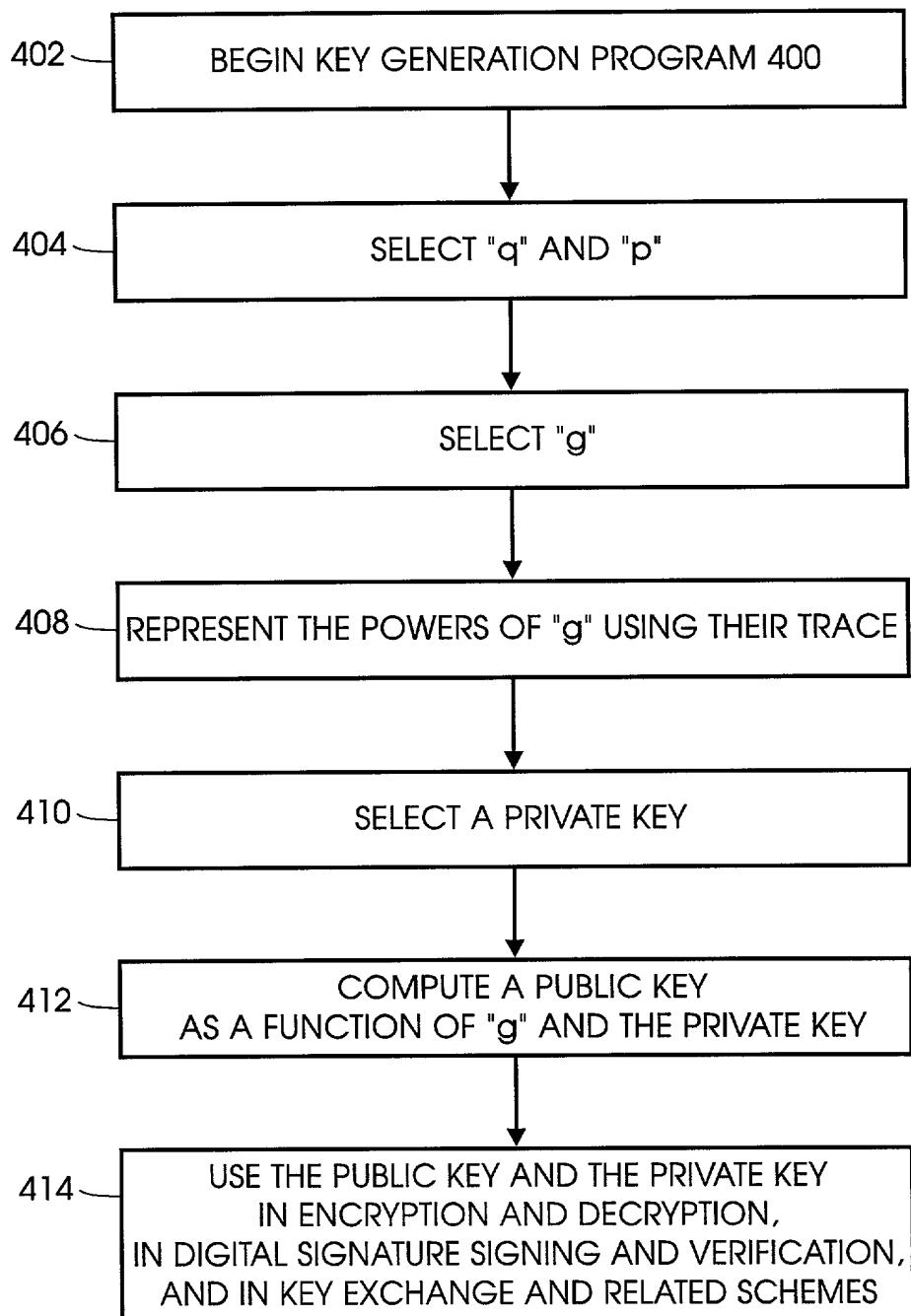


FIG. 4



Let $p \equiv 2 \pmod{3}$ be a prime number such that $6\log_2(p) \approx 1024$ and such that $\phi_6(p) = p^2 - p + 1$ has a prime factor q with $\log_2(q) \geq 160$. Such p and q (or of any other reasonable desired size) can quickly be found by picking a prime $q \equiv 7 \pmod{12}$, by finding the two roots r_1 and r_2 of $x^2 - x + 1 \equiv 0 \pmod{q}$, and by finding an integer k such that $r_i + k*q$ is $2 \pmod{3}$ and prime for $i = 1$ or 2 . If desired, primes q can be selected until the smallest or the largest root is prime, or any other straightforward variant that fits one's needs may be used, for instance to get $\log_2(q) \approx 180$ and $6\log_2(p) \approx 3000$, i.e., $\log_2(p)$ considerably bigger than $\log_2(q)$. From $q \equiv 7 \pmod{12}$ it follows that $q \equiv 1 \pmod{3}$ so that, with quadratic reciprocity, $x^2 - x + 1 \equiv 0 \pmod{q}$ has two roots. It also follows that $q \equiv 3 \pmod{4}$ which implies that those roots can be found using a single $((q+1)/4)^{\text{th}}$ powering modulo q .

By $g \in \text{GF}(p^6)$ we denote an element of order q . It is well known that g is not contained in any proper subfield of $\text{GF}(p^6)$ (cf. [4]). In the next section it is shown that there is no need for an actual representation of g and that arithmetic on elements of $\text{GF}(p^6)$ can be entirely avoided. Thus, there is no need to represent elements of $\text{GF}(p^6)$, for instance by constructing an irreducible 3rd degree polynomial over $\text{GF}(p^2)$. A representation of $\text{GF}(p^2)$ is needed however. This is done as follows.

From $p \equiv 2 \pmod{3}$ it follows that $p \pmod{3}$ generates $\text{GF}(3)^*$, so that the zeros α and α^p of the polynomial $(X^3 - 1)/(X - 1) = X^2 + X + 1$ form an optimal normal basis for $\text{GF}(p^2)$ over $\text{GF}(p)$. Because $\alpha^i = \alpha^{i \bmod 3}$, an element $x \in \text{GF}(p^2)$ can be represented as $x_0\alpha + x_1\alpha^p = x_0\alpha + x_1\alpha^2$ for $x_0, x_1 \in \text{GF}(p)$, so that $x^p = x_0^p\alpha^p + x_1^p\alpha^{2p} = x_1\alpha + x_0\alpha^2$.

Figure 5 is a flow diagram of the method for selection of "p", as shown in section 2.1.

Algorithm for the computation of $T(n)$ given $B = T(1)$. Given B (and B^p), we show how $S(n+1)$ and $S(2n)$ can be computed based on $S(n)$. Computation of $T(n)$ for arbitrary n then follows using the ordinary square and multiply method based on $S(1) = (B^p, 3, B)$ (cf. Definition 2.4.3).

- $S(n+1)$ can be computed from $S(n)$ using Corollary 2.4.2.ii. This takes two multiplications in $\text{GF}(p^2)$.
-
- $S(2n)$ can be computed by first using Corollary 2.4.2.i to compute $T(2n-2)$ and $T(2n)$ given $S(n)$, at the cost of two squarings in $\text{GF}(p^2)$, followed by an application of Corollary 2.4.2.iii to compute $T(2n-1)$ at the cost of two multiplications in $\text{GF}(p^2)$.
-

In both steps we use that p th powering is for free in $\text{GF}(p^2)$.

Figure 6 is a flow diagram of the arithmetic method to support key generation, as shown in section 2.4.4.

Algorithm 3.3.8 for the computation of B .

1. Pick at random an element $B' \in \text{GF}(p^2)^* \setminus \text{GF}(p)^*$;
2. Use Algorithm 2.4.7 with B replaced by B' and T replaced by V to compute $V(p+1)$ (i.e., with $B' = T(1) = V(1)$);
3. If $V(p+1) \in \text{GF}(p)$, then return to Step 1;
4. Use Algorithm 2.4.7 with B replaced by B' to compute $T((p^2-p+1)/q)$ (i.e., with $B' = T(1)$);
5. If $T((p^2-p+1)/q) = 3$, then return to Step 1;
6. Let $B = T((p^2-p+1)/q)$.

Figure 7 is a flow diagram of the method of key generation, as shown in section 3.3.8.

4.1 Application to the Diffie-Hellman scheme

Suppose that two parties, Alice and Bob, who both have access to the public key data p , q , B want to agree on a shared secret key. They can do this by performing the following variant of the Diffie-Hellman scheme:

1. Alice selects at random an integer a , $1 < a < q - 2$, uses Algorithm 2.4.7 to compute $V_A = T(a) \in GF(p^2)$, and sends V_A to Bob.
2. Bob receives V_A from Alice, selects at random an integer b , $1 < b < q - 2$, uses Algorithm 2.4.7 to compute $V_B = T(b) \in GF(p^2)$, and sends V_B to Alice.
3. Alice receives V_B from Bob, and uses Algorithm 2.4.8 with B replaced by V_B (i.e., with $V_B = T(1)$) to compute $K_{AB} = T(a) \in GF(p^2)$.
4. Bob uses Algorithm 2.4.8 with B replaced by V_A (i.e., with $V_A = T(1)$) to compute $K_{AB} = T(b) \in GF(p^2)$.

The length of the messages exchanged in this DH variant is about one third of the length of the messages in other implementations of the DH scheme that achieve the same level of security and that are based on the difficulty of computing discrete logarithms in (a subgroup of) the multiplicative group of a finite field. Also, our variant of the DH scheme requires considerable less computation than those previously published methods (cf. Remark 2.4.10).

Figure 8 is a flow diagram of the method of Diffie Hellman key exchange, as shown in section 4.1, using keys generated by the method of Figure 7.

4.2 Application to the ElGamal encryption scheme

Suppose that Alice is the owner of the public key data p, q, B , and that Alice has selected a secret integer k and computed the corresponding public value $C = T(k)$ using Algorithm 2.4.7. Thus, Alice's public key data consists of (p, q, B, C) . Given Alice's public key (p, q, B, C) Bob can encrypt a message M intended for Alice using the following variant of ElGamal encryption:

1. Bob selects at random an integer b , $1 < b < q - 2$;
2. Bob uses Algorithm 2.4.7 to compute $V_B = T(b) \in \text{GF}(p^2)$;
3. Bob uses Algorithm 2.4.7 with B replaced by C (i.e., with $C = T(1)$) to compute $K = T(b) \in \text{GF}(p^2)$;
4. Bob uses K to encrypt M , resulting in the encryption E .
5. Bob sends (V_B, E) to Alice.

Note that Bob may have to hash the bits representing K down to a suitable encryption key length.

Upon receipt of (V_B, E) , Alice decrypts the message in the following manner:

1. Alice uses Algorithm 2.4.7 with B replaced by V_B (i.e., with $V_B = T(1)$) to compute $K = T(k) \in \text{GF}(p^2)$;
2. Alice uses K to decrypt E resulting in M .

The message (V_B, E) sent by Bob consists of the actual encryption E , whose length strongly depends on the length of M , and the overhead V_B , whose length is independent of the length of M . The length of the overhead in this variant of the ElGamal encryption scheme is about one third of the length of the overhead in other implementations of message-length independent ElGamal encryption (cf. Remark 4.2.1). Also, our method is considerably faster (cf. Remark 2.4.10).

Figure 9 is a flow diagram of the method of ElGamal encryption, as shown in section 4.2, using keys generated by the method of Figure 7.

Algorithm 2.5.3 for the computation of the representation of $g^a * y^b$ for integers a, b with $1 < a, b < q$, given the representation B of g and the representations C, C_+ , and C_- of $y, y*g$, and y/g , respectively.

1. Compute $c = a/b \bmod q$;
2. Given B use Algorithm 2.4.7 to compute $T(c+1), T(c), T(c-1)$ (note that the final applications of Corollary 2.4.2.i in Algorithm 2.4.7, if any, should be replaced by the usual calculation of the full $S(2n)$);
3. Use Lemma 2.5.2 with $T(0) = 3, T(1) = B, T(-1) = B^p, T(c), T(c+1)$, and $T(c-1)$ to compute A^c ;
4. Use Lemma 2.5.2 with $T(0) = 3, T(1) = B, T(-1) = B^p, T(k) = C, T(c+1) = C_+$, and $T(c-1) = C_-$ to compute the corresponding power of A , which we denote by A^k , even though k is unknown;
5. Compute A^{c+k} ;
6. Using Lemma 2.5.1 and A^{c+k} compute $T(c+k)$;
7. Use Algorithm 2.4.7 with B replaced by $T(c+k)$ and n replaced by b to compute the representation $T((c+k)*b) = T(a+k*b)$ of $g^a * y^b$.

Figure 10A is a flow diagram of the arithmetic method to support generating digital signatures, as shown in section 2.5.3.

4.3 Application to digital signature schemes

Let, as in 4.2, Alice's public key data consists of (p, q, B, C) , where $C = T(k)$ and k is Alice's private key. Furthermore, assume that $C_+ = T(k+1)$ and $C_- = T(k-1)$ are included in Alice's public key (cf. 2.5). We show how the Nyberg-Rueppel (NR) message recovery signature scheme can be implemented using our subgroup representation. Application of our method to other digital signature schemes goes in a similar way. To sign a message M containing an agreed upon type of redundancy, Alice does the following:

1. Alice selects at random an integer a , $1 < a < q - 2$;
2. Alice uses Algorithm 2.4.7 to compute $V_A = T(a) \in GF(p^2)$;
3. Alice uses V_A to encrypt M , resulting in the encryption E .
4. Alice computes the (integer valued) hash h of E .
5. Alice computes $s = (k * h + a)$ modulo q in the range $\{0, 1, \dots, q-1\}$.
6. Alice's resulting signature on M is (E, s) .

As in 4.2 Alice may have to hash the bits representing V_A down to a suitable encryption key length.

To verify Alice's signature (E, s) and to recover the signed message M , Bob does the following:

1. Bob obtains Alice public key data (p, q, B, C, C_+, C_-) .
2. Bob checks that $0 \leq s < q$; if not failure.
3. Bob computes the hash h of E (using the same hash function used by Alice).
4. Bob replaces h by $-h$ modulo q (i.e., in the range $\{0, 1, \dots, q-1\}$).
5. Bob uses Algorithm 2.5.3 to compute the representation V_B of $g^s * y^h$ given $a = s$, $b = h$, B , C , C_+ , and C_- .
6. Bob uses V_B to decrypt E resulting in the message M .
7. If M contains the agreed upon type of redundancy, then the signature is accepted; if not the signature is rejected.

Figure 10B is a flow diagram of the method of generating digital signatures, as shown in section 4.3., using keys generated by the method of Figure 7.

**COMBINED DECLARATION AND POWER OF ATTORNEY FOR
ORIGINAL, DESIGN, NATIONAL STAGE OF PCT, SUPPLEMENTAL,
DIVISIONAL, CONTINUATION OR CONTINUATION-IN-PART APPLICATION**

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name,

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

EFFICIENT AND COMPACT SUBGROUP TRACE REPRESENTATION ("XTR")

the specification of which

- a. is attached hereto
- b. was filed on _____ as application Serial No. _____ and was amended on _____. (if applicable).

PCT FILED APPLICATION ENTERING NATIONAL STAGE

- c. was described and claimed in International Application No. _____ filed on _____ and as amended on _____. (if any).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in 37 C.F.R. § 1.56.

I hereby specify the following as the correspondence address to which all communications about this application are to be directed:

SEND CORRESPONDENCE TO:

MORGAN & FINNEGAN, L.L.P.
345 Park Avenue
New York, N.Y. 10154

DIRECT TELEPHONE CALLS TO: 202-857-8011

I hereby claim foreign priority benefits under Title 35, United States Code § 119 (a)-(d) or under § 365(b) of any foreign application(s) for patent or inventor's certificate or under § 365(a) of any PCT international application(s) designating at least one country other than the U.S. listed below and also have identified below such foreign application(s) for patent or inventor's certificate or such PCT international application(s) filed by me on the same subject matter having a filing date within twelve (12) months before that of the application on which priority is claimed:

The attached 35 U.S.C. § 119 claim for priority for the application(s) listed below forms a part of this declaration.

| Country/PCT | Application Number | Date of filing (day, month, yr) | Date of issue (day, month, yr) | Priority Claimed |
|-------------|--------------------|------------------------------------|-----------------------------------|---|
| | | | | <input type="checkbox"/> Y <input type="checkbox"/> N |
| | | | | <input type="checkbox"/> Y <input type="checkbox"/> N |
| | | | | <input type="checkbox"/> Y <input type="checkbox"/> N |

I hereby claim the benefit under 35 U.S.C. § 119(e) of any U.S. provisional application(s) listed below.

Provisional Application No.

Date of filing (day, month, yr)

**ADDITIONAL STATEMENTS FOR DIVISIONAL, CONTINUATION OR CONTINUATION-IN-PART
OR PCT INTERNATIONAL APPLICATION(S DESIGNATING THE U.S.)**

I hereby claim the benefit under Title 35, United States Code § 120 of any United States application(s) or under § 365(c) of any PCT international application(s) designating the U.S. listed below.

| US/PCT Application Serial No. | Filing Date, | Status (patented, pending, abandoned)/ U.S. application no. assigned (For PCT) | US/PCT |
|-------------------------------|--------------|---|--------|
| Application Serial No. | Filing Date, | Status (patented, pending, abandoned)/ U.S. application no. assigned (For PCT) | |

In this continuation-in-part application, insofar as the subject matter of any of the claims of this application is not disclosed in the above listed prior United States or PCT international application(s) in the manner provided by the first paragraph of Title 35, United States Code, § 112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, § 1.56(a) which occurred between the filing date of the prior application(s) and the national or PCT international filing date of this application.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or Imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

I hereby appoint the following attorneys and/or agents with full power of substitution and revocation, to prosecute this application, to receive the patent, and to transact all business in the Patent and Trademark Office connected therewith: John A. Diaz (Reg. No. 19,550), John C. Vassil (Reg. No. 19,098), Alfred P. Ewert (Reg. No. 19,887), David H. Pfeffer (Reg. No. 19,825), Harry C. Marcus (Reg. No. 22,390), Robert E. Paulson (Reg. No. 21,046), Stephen R. Smith (Reg. No. 22,615), Kurt E. Richter (Reg. No. 24,052), J. Robert Dailey (Reg. No. 27,434), Eugene Moroz (Reg. No. 25,237), John F. Sweeney (Reg. No. 27,471), Arnold I. Rady (Reg. No. 26,601), Christopher A. Hughes (Reg. No. 26,914), William S. Feiler (Reg. No. 26,728), Joseph A. Calvaruso (Reg. No. 28,287), James W. Gould (Reg. No. 28,859), Richard C. Komson (Reg. No. 27,913), Israel Blum (Reg. No. 26,710), Bartholomew Verdirame (Reg. No. 28,483), Maria C.H. Lin (reg. No. 29,323), Joseph A. DeGirolamo (Reg. No. 28,595), Michael P. Dougherty (Reg. No. 32,730), Seth J. Atlas (Reg. No. 32,454), Andrew M. Riddles (Reg. No. 31,657), Bruce D. DeRenzi (Reg. No. 33,676), Michael M. Murray (Reg. No. 32,537), Mark J. Abate (Reg. No. 32,527), Alfred L. Haffner, Jr. (Reg. No. 18,919), Harold Haidt (Reg. No. 17,509), John T. Gallagher (Reg. No. 35,516), Steven F. Meyer (Reg. No. 35,613) and Kenneth H. Sonnenfeld (Reg. No. 33,285), Tony V. Pezzano (Reg. No. 38,271), Andrea L. Wayda (Reg. 43,979) and Walter G. Hanchuk (Reg. No. 35,179) of Morgan & Finnegan, L.L.P. whose address is: 345 Park Avenue, New York, New York, 10154; and Michael S. Marcus (Reg. No. 31,727) and John E. Hoel (Reg. No. 26,279) of Morgan & Finnegan, L.L.P., whose address is 1775 Eye Street, Suite 400, Washington, D.C. 20006.

I hereby authorize the U.S. attorneys and/or agents named hereinabove to accept and follow instructions from _____ as to any action to be taken in the U.S. Patent and Trademark Office regarding this application without direct communication between the U.S. attorneys and/or agents and me. In the event of a change in the person(s) from whom instructions may be taken I will so notify the U.S. attorneys and/or agents named hereinabove.

Full name of sole or first inventor Arjen K. Lenstra

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ATTACHED IS ADDED PAGE TO COMBINED DECLARATION AND POWER OF ATTORNEY FOR SIGNATURE BY THIRD AND SUBSEQUENT INVENTORS FORM.

* Before signing this declaration, each person signing must:

1. Review the declaration and verify the correctness of all information therein; and
2. Review the specification and the claims, including any amendments made to the claims.

After the declaration is signed, the specification and claims are not to be altered.

To the inventor(s):

The following are cited in or pertinent to the declaration attached to the accompanying application:

Title 37, Code of Federal Regulation, §1.56

Duty to disclose information material to patentability

(a) A patent by its very nature is affected with a public interest. The public interest is best served, and the most effective patent examination occurs when, at the time an application is being examined, the Office is aware of and evaluates the teachings of all information material to patentability. Each individual associated with the filing and prosecution of a patent application has a duty of candor and good faith in dealing with the Office, which includes a duty to disclose to the Office all information known to that individual to be material to patentability as defined in this section. The duty to disclose information exists with respect to each pending claim until the claim is canceled or withdrawn from consideration, or the application becomes abandoned. Information material to the patentability of a claim that is canceled or withdrawn from consideration need not be submitted if the information is not material to the patentability of any claim remaining under consideration in the application. There is no duty to submit information which is not material to the patentability of any existing claim. The duty to disclose all information known to be material to patentability is deemed to be satisfied if all information known to be material to patentability of any claim issued in a patent was cited by the Office or submitted to the Office in the manner prescribed by §§1.97(b)-(d) and 1.98. However, no patent will be granted on an application in connection with which fraud on the Office was practiced or attempted or the duty of disclosure was violated through bad faith or intentional misconduct. The Office encourages applicants to carefully examine:

- (1) prior art cited in search reports of a foreign patent office in a counterpart application, and
- (2) the closest information over which individuals associated with the filing or prosecution of a patent application believe any pending claim patentably defines, to make sure that any material information contained therein is disclosed to the Office.

Title 35, U.S. Code § 101

Inventions patentable

Whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof, may obtain a patent therefor, subject to the conditions and requirements of this title.

Title 35 U.S. Code § 102

Conditions for patentability; novelty and loss of right to patent

A person shall be entitled to a patent unless --

- (a) the invention was known or used by others in this country, or patented or described in a printed publication in this or a foreign country, before the invention thereof by the applicant for patent,
- (b) the invention was patented or described in a printed publication in this or foreign country or in public use or on sale in this country, more than one year prior to the date of application for patent in the United States, or
- (c) he has abandoned the invention, or
- (d) the invention was first patented or caused to be patented, or was the subject of an inventor's certificate, by the applicant or his legal representatives or assigns in a foreign country prior to the date of the application for patent in this country on an application for patent or inventor's certificate filed more than twelve months before the filing of the application in the United States, or
- (e) the invention was described in a patent granted on an application for patent by another filed in the United States before the invention thereof by the applicant for patent, or on an international application by another who has fulfilled the requirements of paragraphs (1), (2), and (4) of section 371(c) of this title before the invention thereof by the applicant for patent, or
- (f) he did not himself invent the subject matter sought to be patented, or
- (g) before the applicant's invention thereof the invention was made in this country by another who had not abandoned, suppressed, or concealed it. In determining priority of invention there shall be considered not only the respective dates of conception and reduction to practice of the invention, but also the reasonable diligence of one who was first to conceive and last to reduce to practice, from a time prior to conception by the other .

Title 35, U.S. Code § 103

Conditions for patentability; non-obvious subject matter

A patent may not be obtained though the invention is not identically disclosed or described as set forth in section 102 of this title, if the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains. Patentability shall not be negatived by the manner in which the invention was made.

Subject matter developed by another person, which qualifies as prior art only under subsection (f) or (g) of section 102 of this title, shall not preclude patentability under this section where the subject matter and the claimed invention were, at the time the invention was made, owned by the same person or subject to an obligation of assignment to the same person.

Title 35, U.S. Code § 112 (in part)

Specification

The specification shall contain a written description of the invention, and of the manner and process of making and using it, in such full, clear, concise and exact terms as to enable any person skilled in the art to which it pertains, or with which it is most nearly connected, to make and use the same, and shall set forth the best mode contemplated by the inventor of carrying out his invention.

Title 35, U.S. Code, § 119

Benefit of earlier filing date in foreign country; right of priority

An application for patent for an invention filed in this country by any person who has, or whose legal representatives or assigns have, previously regularly filed an application for a patent for the same invention in a foreign country which affords similar privileges in the case of applications filed in the United States or to citizens of the United States, shall have the same effect as the same application would have if filed in this country on the date on which the application for patent for the same invention was first filed in such foreign country, if the application in this country is filed within twelve months from the earliest date on which such foreign application was filed; but no patent shall be granted on any application for patent for an invention which had been patented or described in a printed publication in any country more than one year before the date of the actual filing of the application in this country, or which had been in public use or on sale in this country more than one year prior to such filing.

Title 35, U.S. Code, § 120

Benefit or earlier filing date in the United States

An application for patent for an invention disclosed in the manner provided by the first paragraph of section 112 of this title in an application previously filed in the United States, or as provided by section 363 of this title, which is filed by an inventor or inventors named in the previously filed application shall have the same effect, as to such invention, as though filed on the date of the prior application, if filed before the patenting or abandonment of or termination of proceedings on the first application or an application similarly entitled to the benefit of the filing date of the first application and if it contains or is amended to contain a specific reference to the earlier filed application.

Please read carefully before signing the Declaration attached to the accompanying Application.

If you have any questions, please contact Morgan & Finnegan, L.L.P.